



TASK REPORT 97-03

Second Report for Research and Modeling of Water Particles in Adverse Weather Simulation Facilities

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1.0 INTRODUCTION TO THE RESEARCH

This report describes a continuation of research into the modeling of water particle freezing for application to adverse weather simulation facilities. The research was initiated in FY1996 to investigate the physics of freezing of submillimeter supercooled water particles or droplets in both natural and artificial or simulated adverse weather environments. The first phase of the research was reported and discussed in a report [1] and a paper [2]. The work has continued into FY1997 and has been expanded to include work done to model three-dimensional ice accretions on surfaces, as well as modeling the near field of water spray clouds produced by air-atomized water spray nozzles. Because of the increased scope of the work, a single report cannot cover all of the work phases. Therefore, the present report covers only the continued research and development of water particulate freezing models and their application in a one-dimensional multiphase flow code to predict water spray freezing in ducted air flows.

The outline of the report is as follows:

Section 2 provides an overview of applications of classical homogeneous nucleation theory to predict supercooled water particle freezing. Specifically, it covers and discusses the $J(T)$ and $I(T)$ functions (which are identical except for nomenclature used by various authors) that predict the rate-of-formation of freezing centers or ice-germ nuclei that initiated the freezing process.

Section 3 describes how $J(T)$ and/or $I(T)$ were evaluated in the present study and compared to their evaluations in the literature.

Section 4 describes how $J(T)$ and/or $I(T)$ were modified to apply to the heterogeneous freezing of nominal purity supercooled water droplets.

Section 5 then provides calculated results from incorporating the modified heterogeneous droplet freezing model into the AEDC 1DMP code and evaluating some of the same flow cases

as described in references [1,2] for a ten-droplet water spray. The results from a previously developed simple heterogeneous freezing model and the new modified homogeneous nucleation freezing function model are compared and evaluated.

Section 6 then summarizes the current status of research and development under this phase of the research task investigation, provides conclusions about accomplished and needed future research, and makes recommendations about how to pursue future development of adverse weather simulation test capabilities in ground test facilities.

2.0 OVERVIEW OF CLASSICAL HOMOGENEOUS NUCLEATION THEORY

2.1 Nucleation Probability Functions

This section very briefly reviews the homogeneous nucleation probability functions of the literature and describes the selection process used to select one of the functions for application to development of a heterogeneous freezing model for supercooled water droplets.

In this context, homogeneous nucleation refers to the creation of a condensed phase of a pure substance by the thermodynamically controlled formation of condensed phase precursors. These precursors are metastable clusters of molecules that potentially can serve to trigger the formation of the condensed phase, that is, act as condensation sites. Specifically, the precursors can be thought of as predroplets, or nandroplets, when a liquid condenses from a supersaturated vapor, or as ice germs when ice crystals form within a liquid. Heterogeneous nucleation follows the same thermodynamic process of molecular cluster formation as occurs in homogeneous nucleation, except that some foreign material, such as a particle or a surface, reduces the energy required to form the precursors. Thus, heterogeneous nucleation occurs at higher phase temperatures, in general, than homogeneous nucleation.

The literature on nucleation and condensation processes, that start with the formation of metastable molecular clusters in the non-condensed phase of a substance, is reasonably large in both papers [3-38], and books [39-43]. The "condensed" phase may be a liquid droplet condensing from a (non-condensed) supersaturated vapor, or it may represent a proto-crystal or ice germ, in the case where pure supercooled liquid water is beginning its spontaneous freezing process, at some temperature below 273.16 K. The freezing process that begins to occur in sprays of supercooled liquid metal droplets is essentially the same process as that in which pure supercooled water spray droplets freeze, except that liquid metals can be alloys and can freeze in different solid phases, depending on drop size, composition, and temperature at the time of solidification nucleation. However, pure liquid water droplets, supercooled and freezing, turn into ice I-type solid crystalline particles under normal "atmospheric" conditions.

As stated, the purpose of this section of the report is to briefly overview the probability functions, denoted in the literature as $J(T)$ or $I(T)$, which predict the production rate of nucleation sites per unit volume per unit time. In the present research effort, the theory for homogeneous nucleation of "pure" liquid water droplets, or homogeneous freezing, has been modified to account for heterogeneous (or mote-induced) freezing of water droplets. Heterogeneous freezing is the usual, typical, or most probable freezing process for liquid water of average purity, such as either unfiltered, or even filtered, and distilled drinking water. The modified homogeneous nucleation freezing theory can be applied in a straight-forward way to general numerical spray computation codes (numerical spray CFD codes) that track the position, lifetime, kinetic, and thermal states of particles or particle group packets that are injected and convected in gas flows. Moreover, the modified theory can incorporate probabilistic functions that extend the theory to stochastic processes of freezing. To explain the modified theory, it is necessary to review or overview classical homogeneous nucleation theory for particulate freezing. The theory begins in

Germany with the work of Volmer, et al. [3], Becker, et al. [4], and others with further development by Turnbull, and co-workers, e.g. [7,8]. Its exposition, however, is begun with Mason [14], for convenience.

2.2 Mason (1952)

In his paper, Mason [14] provides $J(T)$ in the form

$$J(T) = \frac{nkT}{h} \exp \left\{ -\frac{U}{kT} - \frac{W_c}{kT} \right\} \quad (1)$$

Mason then evaluates $\log J(T)$ ¹ as

$$\log J(T) = 32.84 + \log T - \frac{U}{2.30kT} - \frac{760\sigma_{sl}^3}{(T_o - T)^2 T} \quad (2)$$

In these expressions, the parameters are:

$n \equiv$ number of molecules per cubic centimeter of the condensed phase,

$k \equiv$ Boltzmann's constant,

$h \equiv$ Planck's constant,

$T \equiv$ the absolute temperature, Kelvins,

$T_o \equiv$ the bulk water freezing temperature, Kelvins (273.16K)

$U \equiv$ the "activation energy for self-diffusion of a molecule in the" non-condensed phase,

$W_c \equiv$ "the work of nucleus formation".

Mason provides W_c as

$$W_c = \frac{1}{3} \sigma_{sl} A = \frac{1}{3} \sigma_{sl} \omega r_c^2 \quad (3)$$

attributing this to Frenkel [39]. These parameters are:

¹ Footnote: $\ln ()$ refers to the natural log, whereas $\log ()$ refers to log base 10.

$\sigma_{sl} \equiv$ the "specific surface energy of the crystal-liquid interface".

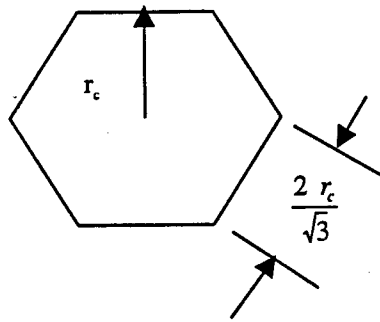
$A \equiv$ the surface area of the nucleus (the molecular cluster, or ice germ precursor).

$\omega \equiv$ shape factor for nucleus, relating the surface to volume ratio for the shape of the cluster (ω is approximately 21 – 23 in value).

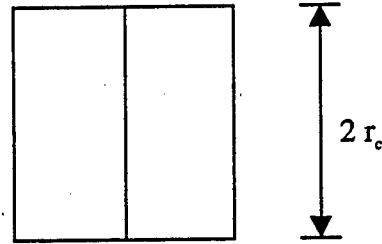
$r_c \equiv$ the radius of a sphere inscribed in a nucleus of critical size, i.e., that sized nucleus that can form a nucleation or crystallization site.

Mason evaluates ω by assuming that the nucleus forms a hexagonal prism with height equal to twice the radius to a prismatic side (see sketch below):

Schematic of Prismatic Ice Germ Nucleus



Top or Bottom View



Side View

The volume of this hexagonal prism is $V = 4\sqrt{3} r_c^3 = 6.9282r_c^3$ (4)

The surface area is $A = 12\sqrt{3} r_c^2 = \omega r_c^2 = 20.785r_c^2$ (5)

The surface to volume ratio is $\frac{A}{V} = \frac{12\sqrt{3} r_c^2}{4\sqrt{3} r_c^3} = \frac{3}{r_c}$ (6)

Note also that A can be written in terms of V as $A = 3^{7/6} 4^{1/3} V^{2/3}$ (7)

So that the derivative dA/dV is

$$\frac{dA}{dV} = 3^{7/6} 4^{1/3} \left(\frac{2}{3}\right) V^{-1/3} = 2 \cdot 3^{1/6} \cdot 4^{1/3} V^{-1/3} \quad (8)$$

Substituting for V

$$\frac{dA}{dV} = 2 \cdot 3^{1/6} \cdot 4^{1/3} / (4\sqrt{3} r_c^3)^{1/3} \quad (9)$$

or

$$\frac{dA}{dV} = \frac{2 \cdot 3^{1/6}}{3^{1/6} r_c} = \frac{2}{r_c} \quad (10)$$

This parameter, dA/dV , is important because Mason, in a later paper [25(1960)], shows that the change in Gibbs Free Energy for a collection containing g molecules that have passed from the liquid phase to form a cluster in the solid phase is

$$\Delta G = (\mu_s - \mu_L)g + A\sigma_{SL} \quad (11)$$

where

μ_L \equiv Gibbs Free Energy of molecule in liquid phase,

μ_s \equiv Gibbs Free Energy of molecule in an ice-like cluster,

g \equiv number of molecules in the cluster.

Mason [25(1960)] defines the critical cluster of molecules as the metastable cluster reached when ΔG achieves a maximum, thus the two conditions

$$\frac{d\Delta G}{dg} = 0 \quad (12)$$

and

$$\Delta G = \Delta G_{\max} \quad (13)$$

define the cluster size when a metastable ice germ (cluster) has formed.

Therefore, for this condition,

$$\frac{d\Delta G}{dg} = 0 = (\mu_s - \mu_L) + \frac{dA}{dg} \sigma_{SL} \quad (14)$$

But,

$$\frac{dA}{dg} = \frac{dA}{dV} \frac{dV}{dg} \quad (15)$$

and

$$V = \lambda g \quad (16)$$

where $\lambda \equiv$ the effective volume, per molecule, in the cluster.

Thus,

$$\frac{dA}{dg} = \frac{dA}{dV} \lambda \quad (17)$$

An evaluation of λ gives

$$\lambda = \frac{W_{mol}}{N_A \rho_s} \quad (18)$$

where

$W_{mol} \equiv$ the molecular weight of ice,

$N_A \equiv$ Avogadro's number,

$\rho_s \equiv$ the density of ice.

Thus,

$$\frac{dA}{dg} = \frac{dA}{dV} \frac{W_{mol}}{N_A \rho_s} \quad (19)$$

Consequently, the condition for metastability of the cluster is

$$(\mu_L - \mu_s) = \frac{dA}{dg} \sigma_{SL} = \frac{\sigma_{SL} W_{mol}}{N_A \rho_s} \frac{dA}{dV} \quad (20)$$

However, Mason, e.g. [1960], shows that

$$\frac{d}{dT}(\mu_L - \mu_s) = -(S_L - S_s) = \frac{L_F^*}{T} \quad (21)$$

where

L_F^* \equiv the heat of fusion, per molecule (treated as a negative quantity),

S_L \equiv the entropy of a molecule in the liquid phase,

S_s \equiv the entropy of a molecule in the ice-like cluster or solid phase.

Thus, by integration

$$(\mu_L - \mu_s) = \int_{T_0}^T \frac{L_F^* dT}{T} \quad (22)$$

and, by substitution, therefore, based on equation (20),

$$(\mu_L - \mu_s) = \frac{\sigma_{SL} W_{mol}}{N_A \rho_s} \frac{dA}{dV} = \int_{T_0}^T \frac{L_F^* dT}{T}. \quad (23)$$

Substituting for dA/dV

$$\frac{\sigma_{SL} W_{mol}}{N_A \rho_s} \frac{2}{r_c} = \int_{T_0}^T \frac{L_F^* dT}{T}. \quad (24)$$

Solving for r_c , and rearranging terms gives r_c as

$$r_c = \left(\frac{2\sigma_{SL}}{\rho_s} \right) \bigg/ \int_{T_0}^T \frac{N_A L_F^*}{W_{mol} T} dT. \quad (25)$$

But, the heat of fusion per unit mass of the liquid is

$$L_F = \frac{N_A}{W_{mol}} L_F^*. \quad (26)$$

Therefore, the equation for the critical radius of the metastable molecular cluster is

$$r_c = \frac{2\sigma_{SL}}{\rho_s \int_{T_o}^T \frac{L_F dT}{T}} \quad (27)$$

The work of formation of the critical metastable cluster which was given by equation (3)

$$W_c = \frac{1}{3} \sigma_{SL} A = \frac{1}{3} \sigma_{SL} \omega r_c^2 \quad (28)$$

can now be written substituting for r_c , as

$$W_c = \frac{4}{3} \omega \frac{\sigma_{SL}^3}{\rho_s^2 \left[\int_{T_o}^T \frac{L_F dT}{T} \right]^2} \quad (29)$$

For the hexagonal prism defined by Mason, we had

$$A = 12\sqrt{3} r_c^2 = \omega r_c^2 \quad (5)$$

hence,

$$\omega = 12\sqrt{3} \quad (30)$$

Therefore, W_c can be written as

$$W_c = \frac{16\sqrt{3} \sigma_{SL}^3}{\rho_s^2 \left[\int_{T_o}^T \frac{L_F dT}{T} \right]^2} \quad (31)$$

However, in his 1952 paper [14], Mason simply introduces an equation for r_c that Mason calls "Thompson's equation," without reference, as

$$r_c = \frac{2 \sigma_{SL}}{\rho_s L_F} \frac{T_o}{T_o - T} \quad (32)$$

Mason later provides a derivation of this equation in his 1957 text, *The Physics of Clouds*, [44].

Clearly, equation (32) is also obtainable from equation (27) when L_F is treated as a constant, by expanding and linearizing the resulting log function. In the previous equation, ρ_s is the density

of the condensed phase, here assumed to be Ice-I, normal ice. By using equations (3), (30), and (32) in equation (1), we can write the equation for $J(T)$ as

$$J(T) = \frac{nkT}{h} \exp \left\{ -\frac{U}{kT} - \frac{\left(\frac{1}{3}\right) \sigma_{SL} \omega}{kT} \left(\frac{2\sigma_{SL}}{\rho_s L_F} \right)^2 \left(\frac{T_o}{T_o - T} \right)^2 \right\}. \quad (33)$$

By using $T_o = 273.16$ K, and simplifying, we get

$$J(T) = \frac{nkT}{h} \exp \left\{ -\frac{U}{kT} - \frac{4}{3} \frac{\sigma_{SL}^3 \omega}{kT \rho_s^2 L_F^2} \left(\frac{273.16}{273.16 - T} \right)^2 \right\}. \quad (34)$$

Equation (2) is equation (34), after some of the parameters have been numerically evaluated. Mason provides values, in his 1952 paper, for the following parameters in $J(T)$, as follows.

The interfacial surface tension, σ_{SL} , was evaluated by Mason as the difference between the surface tension of ice at -40°C and of liquid water at -40°C , that is,

$$\sigma_{SL} = \sigma_s - \sigma_L = 102 \frac{\text{erg}}{\text{cm}^2} - 80 \frac{\text{erg}}{\text{cm}^2}$$

or

$$\sigma_{SL} = 22 \frac{\text{erg}}{\text{cm}^2} = 0.022 \frac{\text{J}}{\text{m}^2}.$$

σ_s was estimated from breaking hydrogen bonds normal to a selected face of an ice crystal.

The value for U was estimated at $U = 3.3 \times 10^{-13}$ erg, or 3.3×10^{-20} J, for $0 \leq T \leq -10^\circ\text{C}$, and this same value taken at $T = -40^\circ\text{C}$. The density of ice and its latent heat of fusion were taken as

$$\rho_s = 0.92 \text{ gm/cm}^3 = 920 \text{ kg/m}^3$$

and

$$L_F = -3.33 \times 10^9 \frac{\text{erg}}{\text{gm}} = -3.33 \times 10^5 \frac{\text{J}}{\text{kg}}$$

The shape factor, ω , was taken by Mason to be $\omega = 23$. (However, it was computed in the present study as about 21 instead.)

The next parameter is the number n of molecules of liquid water per unit volume. This parameter is given by $n = \frac{\rho_L \cdot N_A}{W_{mol}}$ where ρ_L is the liquid density, N_A is Avogadro's number, and

W_{mol} is the molecular weight of water. Thus, for

$$\rho_L = 1 \frac{\text{gm}}{\text{cm}^3},$$

$$N_A = 6.022169 \times 10^{23} \frac{\text{molecules}}{\text{gm-mole}},$$

$$W_{mol} = 18 \text{ gm/gm-mole},$$

$$n \text{ is computed as } n = 3.3456 \times 10^{22} \frac{\text{molecules}}{\text{cm}^3} = 3.3456 \times 10^{28} \frac{\text{molecules}}{\text{m}^3}.$$

The remaining parameters are Boltzmann's constant, k , and Planck's constant, h , given by

$$k = 1.380622 \times 10^{-16} \frac{\text{erg}}{\text{K}} = 1.380622 \times 10^{-23} \frac{\text{J}}{\text{K}}$$

and

$$h = 6.626196 \times 10^{-27} \text{ erg} \cdot \text{s} = 6.626196 \times 10^{-34} \text{ J} \cdot \text{s}.$$

Evaluation of $\log J(T)$

Using these values for the parameters in the $J(T)$ equation Mason evaluated $\log J(T)$ as

$$\begin{aligned} \log J(T) = & \log(3.3456 \times 10^{22}) + \log(1.380622 \times 10^{-16}) + \log T - \log(6.626196 \times 10^{-27}) \\ & - \frac{U}{2.303 kT} - \frac{4}{3} \cdot \frac{1}{2.303} \cdot \frac{\sigma_{SL}^3 (23)(273.16)^2}{(1.380622 \times 10^{-16}) T (0.92)^2 (3.33 \times 10^9)^2} \cdot \frac{1}{(T_o - T)^2}. \end{aligned} \quad (35)$$

Evaluating this, we get

$$\log J(T) = 32.843 + \log T - \frac{U}{2.303kT} - \frac{766.8\sigma_{SL}^3}{T(T_0 - T)^2} \quad (36)$$

where σ_{SL} is in erg/cm² units and $J(T)$ would be in units of nuclei per cubic centimeter per second. With minor numerical differences, this is Mason's equation, equation (2).

In the present study, using the values of the parameters as given in SI units, and using natural logarithms, this equation has been put into the form

$$\ln J(T) = 89.440 + \ln T - \frac{2390.2}{T} - \frac{252}{T} \left(\frac{273.16}{273.16 - T} \right)^2 \quad (37)$$

Alternately, this equation gives $J(T)$ as

$$J(T) = 6.9708 \times 10^{38} T \exp \left\{ -\frac{2390.2}{T} - \frac{252}{T} \left(\frac{273.16}{273.16 - T} \right)^2 \right\} \quad (38)$$

with units of nuclei per meter cubed per second.

In the following subsections of the report, alternate forms for $J(T)$ are described which are given in the literature. $J(T)$ has been also given the symbol $I(T)$. In this report, $J(T)$ and $I(T)$ are exactly the same functions.

2.3 McDonald (1953)

In this paper, McDonald [18] provides a critical review of homogeneous nucleation theory. In particular, with reference to the application of the theory to predict the spontaneous freezing of supercooled submillimeter water droplets by homogeneous nucleation, McDonald reviews and assesses the values of the physical parameters in the argument of the function, $J(T)$. McDonald writes the $J(T)$ function as (with a sign correction).

$$J(T) \approx \frac{nkT}{h} \exp \left\{ - \left(\frac{A + F_c}{kT} \right) \right\} \quad (39)$$

A is the activation energy for self-diffusion of liquid molecules near the water-ice germ interface. F_c is the work of formation of the ice germ or molecular cluster. n is the number of molecules per unit volume in the liquid phase, k is Boltzmann's constant, and h is Planck's constant.

McDonald gives F_c as

$$F_c = \sigma_s g r_c^2 / 3 \quad (40)$$

where r_c is the critical radius of the molecular cluster, given by

$$r_c = \frac{2\sigma_s T_o}{(\rho_s L_F (T_o - T))} \quad (41)$$

In these equations, σ_s is the specific surface free energy of the water-ice germ interface, g is a geometric factor such that $g r_c^2$ is the total surface area of the ice germ or critical embryo, ρ_s is the density of ice, L_F is the latent heat of fusion of ice, and T_o is the melting temperature of ice, 273.16 K. Thus, the expression for $J(T)$ is essentially the same as that presented earlier by Mason and co-workers.

The main thrust of McDonald's investigation is an examination of the parameters A , σ_s , and L_F . McDonald reviews the work of others, including Mason [14], in an attempt to obtain thermodynamically correct values of these parameters, in terms of the best theoretical model of an ice germ structure. McDonald notes that L_F , the heat of fusion of ice is not constant, but decreases with decreasing temperature. (This was discussed by the present author in previous work [1, 2].) McDonald also finds both A and σ_s to vary with temperature.

McDonald's rigorous analysis is well worth examination by those with expertise in molecular physics because the levels of uncertainty in the estimations or calculations of A , σ_s , and L_F , that McDonald demonstrates, implies that serious further theoretical and experimental

research is required to put homogeneous nucleation theory on a rigorous basis. This is one of McDonald's main conclusions in 1953 and it appears to be valid even at present. In actual practice, therefore, the application of the freezing function $J(T)$, by Mason and others, is a correlative theory, rather than a predictive theory, due to the uncertainties in the physical parameters of the theory.

2.4 Day (1958)

J. A. Day [21] presented a functional form for $J(T)$ that he attributed to J. B. McDonald [18]. This equation is

$$J(T) = \frac{nkT}{h} \exp \left\{ -\frac{A}{kT} - \frac{30.7\sigma_{SL}^3}{k\rho_s^2 L_F^2 T \left(\ln \frac{T_o}{T} \right)^2} \right\} \quad (42)$$

where T_o and the other parameters have been defined in the previous section. Obviously, this equation can be developed from equation (1) with W_c evaluated from equation (31) and with L_F treated as constant.

2.5 Mason (1958)

Mason presented another version of the $J(T)$ equation in this 1958 paper [22]. In this paper, Mason uses $I(T)$ to represent the nuclei density rate equation. The equation provided was

$$\log I(T) = 32.84 + \log T - \frac{U}{2.303kT} - \frac{1.11 \times 10^{17} \sigma_{SL}^3}{L_F^2 T \left(\ln \frac{T_o}{T} \right)^2} \quad (43)$$

The same comments apply here to this equation as for the equation Day presented.

2.6 Langham and Mason (1958)

In 1958, Langham and Mason reviewed the heterogeneous and homogeneous nucleation of supercooled water [23] and presented a functional equation for $I(T)$ that is the same as that of Mason (1958) [22].

2.7 Mason (1960)

In a 1960 paper, Mason [25] applied nucleation theory to predict both the formation of water aerosol droplets from supersaturated water vapor, and also, homogeneous nucleation or freezing of supercooled water droplets. Mason also reviews the formation of water droplets by condensation of vapor on foreign nuclei such as ions, hygroscopic and non-hygroscopic motes, and on "mixed" nuclei.

Mason attributes the theoretical development of condensation theory to Becker and Doring [4], Zeldovich [45], and Turnbull and Fisher [7]. Mason discusses the validity of the theory, as well as the validity of the experiments that provided data on droplet condensation and freezing.

Mason discusses the freezing of submillimeter supercooled droplets by both heterogeneous and homogeneous nucleation processes and the applicable theories for both. Mason also reviews the effectiveness or activity of various mineral substances to act as ice nucleating motes. The most active substance Mason found was silver iodide which Mason says produces one ice crystal per 10000 AgI particles. This statement has relevant implications, therefore, in the interpretation of $J(T)$. It implies that the population number densities for nucleation, as correlated by $J(T)$ (or $I(T)$) must reflect only the active or effective nuclei, or the active/effective motes, and not the actual or physical nuclei/mote population number densities or their rates of creation. Especially this will be true if $J(T)$ is used to predict heterogeneous freezing by correlating the $J(T)$ function (actually σ_{sl}) to a given set of experimental data.

A derivation of $I(T)$ was provided by Mason in this paper [25] that leads to the equation

$$\log I(T) = 32.84 + \log T - \frac{U}{2.303kT} - \frac{16\sqrt{3}\sigma_{SL}^3}{2.303\rho_s^2 kT \left[\int_T^{T_0} \frac{L_F}{T} dT \right]^2} \quad (44)$$

It is clear that this equation can be derived from the approach described in section 2.2 of the present study. In discussing this equation, Mason notes that σ_{SL} probably cannot be calculated with sufficient accuracy to permit using $I(T)$ to predict freezing nucleation rates. However, he also notes, that by using experimental data for the freezing of pure supercooled water droplets, σ_{SL} values can be obtained by correlating $I(T)$ with appropriate sized drops freezing at measured temperatures. If the presence of motes in ordinary water acts to change the σ_{SL} values, then it should also be possible to correlate $I(T)$ to the heterogeneous freezing of supercooled droplets and obtain σ_{SL} versus drop size for each set of experimental data. This has been done in the present research investigation to obtain a $J(T)$ function applicable to heterogeneous nucleation freezing of supercooled water droplets and will be presented in section 4.

2.8 Fletcher (1960)

In this paper [24], Fletcher writes the nucleation site population density function as

$$J(T) = K \exp\{-\Delta G^*/kT\} \quad (45)$$

where “ K is a kinetic constant typically of order $10^{25} \text{ cm}^3 \text{ sec}^{-1}$ for the cases which we shall consider,” k is Boltzmann’s constant, and T is absolute temperature, as utilized previously. Fletcher discusses the extension or application of nucleation/condensation theory to account for the effect of foreign surfaces or particles in modifying (reducing) the value of the work of formation of the molecular cluster or embryo nuclei, denoted ΔG^* . Thus, if a theoretical model can be developed of how substances, either as motes or surfaces, can change the value of ΔG^* , then this model can be incorporated into $J(T)$ to create a heterogeneous nucleation site population

rate equation. Theoretically, therefore, as Becker, Turnbull, Mason, and others have also discussed, heterogeneous nucleation freezing of supercooled water droplets can be predicted with the same theoretical tools used to predict homogeneous freezing of submillimeter supercooled water droplets.

Fletcher discusses the effects of foreign surface geometry and size on ΔG^* for heterogeneous nucleation or the formation of the ice germ or embryo. He presents a function, $f(m,x)$, that modifies the free energy of formation for homogeneous nucleation, i.e., Fletcher gives

$$\Delta G^* = \Delta G_o^* f(m,x) \quad (46)$$

where ΔG_o^* is the free energy of formation of a nucleus of critical radius under homogeneous nucleation conditions, such as given by equation (31) and where

$$m = \cos \theta. \quad (47)$$

Cosine θ is the cosine of the contact angle between ice germ (embryo) and the foreign particle and x is defined as

$$x = R/r^*. \quad (48)$$

R is the radius of a spherical foreign particle and r^* is the radius of curvature of the surface of the critical embryo.

Fletcher [24] provides distributions of $f(m,x)$ in a figure (Fig. 1 of [24]) obtained from solving the "nucleation equations for a spherical cap embryo nucleating upon a perfect spherical particle." Details of this model are provided by Fletcher in another paper.

Fletcher shows that this theoretical model for accounting for the effects of foreign particles on the freezing of supercooled water predicts the correct trends when applied to silver iodide particles inducing higher spontaneous freezing temperatures in supercooled droplets of

water. Thus, the use of modified homogeneous freezing theory to predict heterogeneous freezing can be justified by more than one theoretical approach.

2.9 Kuhns and Mason (1968)

This paper [29] continues the work of Mason on the assessment and theoretical evaluation of the freezing of submillimeter supercooled droplets of pure water. Kuhns and Mason review and describe the work of Mason (1957, 1958, 1960) and others who have studied the freezing of small water droplets. Kuhns and Mason report experimental data they obtained on freezing of freely falling water drops, noting that much of the existing data to 1968 consisted of freezing droplets that were supported or in contact with surfaces, wires, hypodermic needles, etc. Much of this paper describes the apparatus used by Kuhns and Mason to perform their experiments and to analyze the freely falling droplets to estimate their temperature time history, as well as, size. They also investigated the effect of different ambient gases surrounding the particles on the particle freezing process.

These authors review, and apparently expand, the heterogeneous freezing theory of Bigg [16], as well as, the homogeneous theory developed by Mason (1952, 1958, 1960) from the Turnbull-Fisher work [7]. They report the same $J(T)$ function that Mason presented in his 1960 paper (see section 2.7 of the present report). Based on the probability theory of Bigg [16], and using the concept of a "median" freezing temperature for a group of drops all of the same size, but freezing stochastically about this median temperature, the authors define the "median" freezing event as occurring when the product of $J(T_f)$, particle volume, V , and time, t , reach a critical value. That is, when the freezing probability, P_f , reaches $P_f = \frac{1}{2}$, half of the drops are assumed frozen, [16]. To illustrate this theory, let the probability of a drop remaining liquid be given by

$$P_L = 1 - e^{-J(T)Vt}$$

Then, the probability of freezing is

$$P_F = 1 - P_L = e^{-J(T)Vt}$$

Taking the logs of both sides

$$\ln P_F = \ln(1 - P_L) = -J(T)Vt$$

If the probability of freezing of half of the droplets in a given size group is set at $\frac{1}{2}$, then by definition, the drop size group has reached its "median freezing temperature, T_F ". Hence,

$$-\ln P_F = J(T_F)Vt = -\ln(1 - P_L) = -\ln\left(\frac{1}{2}\right) \approx 0.7. \quad (49)$$

The present author utilizes equation (49) differently. Equation (49) can be interpreted or utilized in several ways. With σ_{SL} determined, equation (49) can be used to predict the freezing temperature, T_F , of different sized droplets. Alternately, if the "median" freezing temperature, T_F , of a given sample of drops of all the same size is known, then equation (49) can be used to evaluate a "median" value for σ_{SL} . However, the present author interprets equation (49) somewhat differently.

There are two reasons for the present author using a different interpretation to the product, JVt . From a physical interpretation, the number, N_c , of (active) freezing nuclei present in a single sample or droplet of supercooled water at time, t , must be given by the following integral

$$N_c(t) = \int_{t_0}^{t_F} J(T, D, t) V(D, t) dt \quad (50)$$

where t_F is the time at which the particle begins to freeze, and t_0 is the time at which the particle first began to supercool (the time when its temperature reached 273.16K). In this integral, the function, J , which gives the population net rate-of-creation, has been generalized to be a function

not only of particle temperature, T , but also of particle size, given by its diameter, D , and time, t . Thus, equation (50) can apply equally well to heterogeneous nucleation events in supercooled water.

With this interpretation, the minimum or critical value for N_c is unity, that is, for a single drop undergoing freezing,

$$N_{c,critical} \equiv 1.0 \quad (51)$$

Hence, by the present author's interpretation at least one active freezing site must come into existence in each sample to initiate freezing.

The second reason for this interpretation is that the freezing model must be implemented, in the present study, into a code wherein all droplets of the same size freeze at the same time. At present, the limitations of the code preclude modeling wherein half of the droplets of a given size freeze at the median freezing temperature and half remain liquid. Hence, when a defined measure of the product JVt reaches a critical value for the droplets of that size class, assumed in this study to be unity, all of these droplets begin to freeze. The measure of JVt used in the present study is an integral of the product $JV dt$, as defined below.

In the present study, a criterion or a measure of JVt for both homogeneous and heterogeneous nucleation freezing was adopted, given by the integral equality

$$\int_{t_0}^{t_F} J(T, D, t) V(D, t) dt = 1.0 \quad (52)$$

When this integral reaches unity, all drops of size D are assumed to begin freezing. This criterion (equation (52)) was adopted and has been applied in the present research study to predict heterogeneous nucleation freezing of water spray droplets in ducted air flow, by being incorporated into a numerical model for one-dimensional, multiphase flow described in a previous report [1], and paper [2]. Details of this model are presented later in the present report.

Returning to a discussion of the Kuhns and Mason paper, Kuhns and Mason determine the value of σ_{SL} required in $J(T)$ by requiring 20-micron drops to freeze at a median freezing temperature of -37C after a period of 1 second. This resulted in a σ_{SL} value of

$$\sigma_{SL} = 19.7 \frac{\text{erg}}{\text{cm}^2} = 0.0197 \frac{\text{J}}{\text{m}^2} \quad (53)$$

where σ_{SL} is the same free energy of the ice-water interface or surface as described previously. With this set of conditions, with σ_{SL} of 19.7 erg/cm², the other freezing temperatures of droplets of different sizes can be determined when

$$J(T_{Fi}) V_i(1\text{sec}) = 0.7 \quad (54)$$

where

$T_{Fi} \equiv$ spontaneous (median) freezing temperature of droplets of diameter, d_i

$V_i \equiv \frac{\pi}{6} d_i^3$, the droplet volume for a drop of diameter, d_i .

They presented the resulting T_{Fi} vs d_i curve and compared experimental data from various sources against it, including their own data. The results of the comparison were good.

Kuhns and Mason also estimate the size of the critical embryo, or nucleus or ice germ that reaches a metastable equilibrium, and thus has an opportunity to nucleate the freezing process. The critical radius of the cluster was given by the same equation as equation (27), namely

$$r_c = \frac{2\sigma_{SL}}{\rho_s \int_{T_c}^{T_s} \frac{L_f dT}{T}} \quad (55)$$

where, as before,

$\rho_s \equiv$ the density of ice,

$L_f \equiv$ the heat of fusion (or melting) of ice, (now, however, treated as positive).

If L_f is constant, r_c is given by

$$r_c = \frac{2\sigma_{sl}}{\rho_s L_f \ln \left\{ \frac{T_o}{T} \right\}} \quad (56)$$

By assuming different values of σ_{sl} , the corresponding values of the critical radius r_c were computed, and the number of water molecules that form the ice precursor or embryos were estimated. The authors obtained 150-300 water molecules depending on σ_{sl} in the temperature range investigated. The authors also showed, albeit with some approximation, that the results of a statistical thermodynamics model of water molecule aggregates, termed the "flickering cluster" model, explored by Nemethy and Scheraga [46], can be interpreted to predict the same number of molecules required for a meta-molecular cluster and for a σ_{sl} value of about 20 erg/cm². Thus, it is implied that the methods of statistical thermodynamics, applied to a special model of molecular aggregates, could be used to predict the spontaneous freezing of pure supercooled water.

2.10 Anderson, Miller, Kassner, Jr., and Hagen (1980)

This paper [33] reviews condensation-freezing nucleation of small water droplets in an expansion cloud chamber. The authors report on their experimental cloud chamber test results where submillimeter liquid droplets first nucleate from a supersaturated vapor phase then undergo spontaneous homogeneous (nucleation) freezing. The freezing process is reported to occur where chamber temperature is "near -40°C." The authors also note minor effects of an electric field applied to the cloud chamber which reduces the presence of ions on which droplets can nucleate and thus freeze.

The authors investigate whether the occurrence of frozen nuclei in cold supersaturated vapors is due to the direct formation of ice germs or ice nuclei by vapor to solid nucleation processes or whether it occurs due to a two-step process of nucleation of vapor first to form liquid droplets, then, second, for the liquid droplets to freeze by liquid to solid nucleation. An understanding of which of these processes can account for the presence of atmospheric ice particles would improve our general knowledge about the mechanisms of formation of arctic precipitation clouds.

The authors discuss the literature on water nucleation, including vapor to liquid, vapor to solid, and liquid to solid nucleation. They provide expressions for two nucleation site creation rate functions, $J_{vl}(T)$ and $J_{vs}(T)$. $J_{vl}(T)$ is the homogeneous nucleation site creation rate of liquid water droplets forming by nucleation from supersaturated water vapor. $J_{vs}(T)$ is the homogeneous nucleation site creation rate, per unit volume, for the creation of solid ice particles directly from supersaturated water vapor by homogeneous nucleation. These functions are not presented herein, since it is the $J(T)$ function for nucleation of ice from liquid water (i.e. $J_{ls}(T)$) that is of interest herein. This function was reported in a following paper.

This important paper presents experimental data on nucleation rates of droplets condensing from supersaturated cloud chamber environments, and also, confirms that small submicron and micron sized liquid droplets spontaneously freeze, in about 0.01 seconds, when suddenly formed and environmentally exposed to temperatures at or below -41°C . Other aspects, results, and observations of this paper will not be reviewed herein.

2.11 Hagen, Anderson, and Kassner, Jr. (1981)

This paper [34] is a continuation of the work presented in Anderson, et al., (1980), described in 2.10. In their 1981 paper, Hagen, et al., continue to analyze experimental data on ice nucleation to gain a better understanding of ice nucleation rates, as well as, better estimates of

the free energy of formation of ice germ embryos, under conditions of homogeneous nucleation, i.e., the nucleation of ice from pure supercooled water.

The authors discuss the important role of homogeneous nucleation in the ultimate objective of understanding heterogeneous nucleation. The authors present the $J(T)$ function for the nucleation rate of ice germs, or ice precursors, or ice embryos, from pure supercooled liquid as $J_{LS}(T)$, in the form

$$J_{LS}(T) = n'v \left(\frac{4\sigma_{LS}}{kT} \right)^{\frac{1}{2}} \left(\frac{n_L kT}{h} \right) \exp \left\{ -\frac{\Delta g}{kT} - \frac{\Delta G_{LS}^*}{kT} \right\}. \quad (57)$$

The parameters of this equation are defined as:

$n' \equiv$ the number of molecules of water in contact with a unit area of the ice germ surface,

$v \equiv$ the volume of a water molecule in ice,

$\sigma_{LS} \equiv$ the interfacial free surface energy of an ice and water interface,

$n_L \equiv$ the number of liquid water molecules per unit volume,

$\Delta g \equiv$ the activation energy for the transfer of a water molecule across the water-ice boundary,

$\Delta G_{LS}^* \equiv$ the increase in free energy of the system (of molecules) of a critical-sized embryo, i.e. an embryo that is metastable enough to become an ice germ or ice precursor.

The parameters k and h are the Boltzmann constant and the Planck constant, respectively. The expression for ΔG_{LS}^* was given as

$$\Delta G_{LS}^* = \frac{16\pi\sigma_{LS}^3}{\left[3 \left(n_s kT \ln \left\{ \frac{P_L}{P_s} \right\} \right)^2 \right]} \quad (58)$$

where

$n_s \equiv$ the number of ice molecules per unit volume,

$P_L \equiv$ the saturated vapor pressure of water over a plane surface of liquid water,

$P_s \equiv$ the saturated vapor pressure of water over a plane surface of ice

This form for $J_{LS}(T)$ was ascribed to the theoretical developments of Turnbull and Fisher [7], Dufour and Defay [47], and Hobbs [48].

The authors note that small, 1-20 μm diameter drops, were found to freeze in time scales of order 0.01 seconds, when exposed to ambient temperatures at or below about -40°C .

By applying nucleation theory to fit the freezing populations in their cloud/expansion chamber experiments, Hagen, et al., determine the "energy barrier for freezing" as a set of empirical fits for $\Delta g + \Delta G_{LS}^*$, based on the minimum temperature achieved in each experiment.

Then, an averaged fit for $\Delta g + \Delta G_{LS}^*$ was obtained by least squares, over all the experiments, as

$$\Delta g + \Delta G_{LS}^* = -1.739234 \times 10^{-8} + 8.1157 \times 10^{-21} T \quad \text{J} \quad (59)$$

in units of joules, for temperature in Kelvins. The authors present a figure (Fig. 6, [34]) wherein Δg has been separately estimated as a function of T , given by

$$\Delta g = -71.8 \times 10^{-20} + 0.3400 \times 10^{-20} T \quad \text{J} \quad (60)$$

where Δg has units of joules, and T is in Kelvin.

Note the Δg is the same as the parameter U in the equations for $J(T)$ or $I(T)$ that Mason and co-workers have published, or the parameter A of McDonald [18]. Values for Δg , U or A range from 3.3×10^{-20} J (Mason [14]), to about 9.4×10^{-20} J (Hagen, et al., [34]). Note that

McDonald also discussed a range of values for Δg (or, A) that he estimated [18] as being from about 2.35×10^{-20} to about 5.5×10^{-20} J. Hagen, et al., discussed the differences in the various values of Δg and the differences of interpretation of Δg . The authors note that Δg , determined from experiments in homogeneous nucleation, can be used without modification for application to predicting heterogeneous nucleation events.

The authors incorporate their empirical fit of $\Delta g + \Delta G_{LS}^*$ into the expression for $J_{LS}(T)$, the homogeneous nucleation freezing nuclei rate equation, to get

$$J_{LS}(T) = J(T) = 5.92 \times 10^{32} T \exp \left\{ \frac{1.260 \times 10^5}{T} - 588.1 \right\} \quad (61)$$

which has units of nuclei per cubic centimeter per second. The authors show a plot [their Fig. 7] of $\log_{10} J_{LS}(T)$ versus ambient temperature, covering the range of their experiments, and even extrapolating the curve to greater ambient temperatures. Also plotted was a $J(T)$ function attributed to McDonald [18], which does fall within part of their data in the lower temperature range. However, it is not clear to the present author that Hagen, et al., have interpreted the experimental data appropriately. The interpretation, and the evaluation of the $J(T)$ function in the present authors opinion, should be based on the product $J(T)Vt$, or its integral, which reflects not only the thermodynamic requirements of nucleation, but also reflects the size of the droplet through its volume, as well as the time spent before nucleation, t . Furthermore, in the present author's opinion, when fit to experimental data, the product, $J(T)Vt$, must reflect the active or effective nucleation sites, i.e., those that lead to actual droplet freezing, not to just theoretical population rates. That is, the nucleation population-rate density function when correlated to experiment, must subsequently predict actual, effective freezing site population rates, not theoretical population rates.

In summary of this paper, it's importance includes the fact that the authors analyze the energy requirements for homogeneous nucleation freezing of small (generally less than 1 micron) water droplets formed by condensation from a supersaturated vapor cloud produced in a cloud/expansion chamber. Their analysis shows that homogeneous as well as heterogeneous nucleation freezing of water droplets can be fit by empirical functions for Δg (or U or A) and ΔG_{LS}^* (or W_c). Thus, the present author's opinion is that when such correlations fit the product $J(T)Vt$ to actual freezing data, the fit must reflect the production rate of effective or active freezing nuclei, not just the total population rate of production.

2.12 Jensen, Toon, and Hamill (1991)

This paper [35] represents another instance wherein homogeneous nucleation freezing theory is modified to predict the reduction in the freezing temperature of atmospheric icing clouds by dissolved sulfuric and nitric acids and/or their hydrates in the supercooled droplets. The work also relates directly to understanding polar atmospheric cloud formation.

The authors review classic homogeneous nucleation theory, presenting a form of $J(T)$ derived in Pruppacher and Klett's classic text Microphysics of Clouds and Precipitation [49], namely

$$J(T) = 2 N_c \left(\frac{\rho_w}{\rho_i h} \right) (\sigma_{iw} kT)^{1/2} \exp \left\{ -\frac{\Delta F^+}{kT} - \frac{\Delta F_g}{kT} \right\} \quad (62)$$

in units of nuclei per cubic centimeter per second. The variables are:

N_c \equiv number of water molecules in contact with a unit surface area of the ice germ, embryo, or ice precursor molecular cluster.

ρ_w \equiv density of liquid water.

ρ_i \equiv density of (normal) ice.

σ_{iw} \equiv the surface energy of the ice-water interface.

ΔF^* \equiv the energy that must be overcome for the free water molecules to become bound to the ice crystal precursor;

ΔF^* is equal to the difference between the equilibrium energy of the water molecule in the liquid state, and the energy of the water molecule in the ice phase. This quantity has been called the phase change activation energy or just the activation energy, and has been approximated by the energy of activation for the displacement of water molecules in bulk water. ΔF^* has been given the symbol Δg by Hagen, et al.. [34], U by Mason [14], and A by McDonald [18].

ΔF_g \equiv the work against surface forces required to form a critical ice germ of a metastable size, that can become an ice crystal or ice germ, or embryo.

Jensen, et al., give ΔF_g as

$$\Delta F_g = \frac{4}{3} \pi \sigma_{iw} a_g^2 \quad (63)$$

where

a_g \equiv the radius of the critical nucleus or ice germ. (the same as r_c , before).

The expression for a_g given was

$$a_g = \frac{2M_w \sigma_{iw}}{L_m \rho_i \ln \left\{ \frac{T_o}{T_e} \right\}} \quad (64)$$

where

M_w \equiv the molecular weight of water

L_m \equiv the latent heat of fusion of water (treated as positive)

T_o \equiv the melting temperature of ice (273.16 K)

T_e \equiv the ambient (supercooled) temperature

These two expressions for ΔF_g and a_g are the same as that provided by, for example, Mason [14] (1960), for W_c and r_c , respectively.

Jensen, et al., report that a_g is modified by acids or acid hydrates present or in solution with the water, so that, based on the theory of Pruppacher and Klett [49], for this case

$$a_g = \frac{2 M_w \sigma_{i/s}}{L_m \rho_i \ln \left\{ \frac{T_o}{T_e} \right\} + \rho_i RT \ln a_w} \quad (65)$$

where

$\sigma_{i/s} \equiv$ the "ice-solute surface energy,"

$a_w \equiv$ the activity of water in the solution of water and acid.

Because a_w was reported, experimentally, over a fairly wide temperature range, Jensen, et al., could determine the variation of $J(T)$ over the range of polar cloud temperatures for typical droplet sizes. The spontaneous freezing temperature of droplets now varies with the concentration of acid (such as H_2SO_4) present in solution. Freezing temperatures for solution droplets are predicted as low as 195K or $-78C$.

While this paper has other important results and conclusions concerning the applicability of modified classical homogeneous nucleation theory to predict the freezing of the atmospheric aerosol, these will not be reviewed here. The main point of the present review is merely to document the form for $J(T)$ used by the authors and the method used to modify the function to account for the effects of dissolved material in water to modify the spontaneous freezing temperature of very small, ~ 1 micron, aerosol droplets.

2.13 Stoyanova, Kashchiev, and Kupenova (1994)

This paper [36] develops and tests a method for analyzing and predicting the kinetics of supercooled droplet freezing that encompasses both homogeneous and heterogeneous (seeded)

nucleation freezing. Classical homogeneous nucleation theory is the starting point for the kinetic freezing model. The aim of the paper is "to propose a method for experimental determination of the nucleation rate in freezing droplets, to employ the method for obtaining the ice nucleation rate, to characterize quantitatively the nucleation activity of the aerosols, and to verify the theoretically expected linear dependence of the nucleation rate on the aerosol concentration."

The theoretical considerations begin with the assumption that for each resulting frozen drop, one ice germ or embryo was formed that lead to the frozen drop. Under this hypothesis, if the population of a sample of initially N_o identical drops is studied while being uniformly supercooled at a rate, q , then the time rate of increase in frozen droplets should be functionally related to $J(T)$ (for both homogeneous as well as heterogeneous freezing processes). Stoyanova, et al., show that time can be eliminated as a variable of the problem as follows. If $dN(t)/dt$ is the time-rate-of-change of the number of frozen droplets, then, from the definition of $J(t)$,

$$\frac{dN(t)}{dt} = v[N_o - N(t)]J(t) \quad (66)$$

where v is the volume of each identical droplet. For a constant cooling rate q , by definition

$$\frac{dT}{dt} = -q. \quad (67)$$

Next, the time-rate-of-change of the number of drops freezing can be written

$$\frac{dN(t)}{dt} = \frac{dN(t)}{dT} \frac{dT}{dt} = v[N_o - N(t)]J(t) \quad (68)$$

or, substituting for dT/dt and rearranging

$$\frac{dN(T)}{dT} = -\frac{v}{q}[N_o - N(T)]J(T). \quad (69)$$

Integrating this expression from the initial temperature, $T_o = 273.16\text{K}$, to some supercooled temperature, T , gives

$$N(T) = N_o \left\{ 1 - \exp \left\{ -\frac{v}{q} \int_T^{T_o} J(T^*) dT^* \right\} \right\}. \quad (70)$$

Note that $N(T_o) \equiv 0$, i.e. there were no frozen droplets at $T_o = 273.16$ K.

Stoyanova, et al., then solve this equation for $J(T)$ by first rearranging the terms, and then differentiating with respect to T to get

$$J(T) = \frac{q}{v} \frac{d}{dT} \ln \left\{ 1 - \frac{N(T)}{N_o} \right\} \quad (71)$$

This equation "shows that the experimental determination of the temperature dependence of the nucleation rate J at known droplet volume and constant cooling rate q reduces to finding the temperature derivative of the experimentally obtainable quantity $\ln(1 - N(T)/N_o)$." Also, this procedure applies whether the droplets contain motes or foreign particles or not. Thus, $J(T)$ for heterogeneous nucleation/droplet freezing events can also be experimentally determined. The authors also remark that this method of determining $J(T)$ can also be applied to non-steady-state nucleation processes.

The authors next review classical nucleation theory and present $J(T)$ in the form

$$J(T) = A(T) \exp \{ -W^* / kT \} \quad (72)$$

where

$W^* \equiv$ "the nucleation work,"

$A(T) \equiv$ "a kinetic factor whose temperature dependence is usually weaker than that of the exponential term."

k is the Boltzmann constant as defined in a previous subsection. The authors note that $J(T)$ is really $J(T(t))$ or $J(t)$, since the phase temperature usually depends on time. Application of the classical theory is valid for relatively slow temperature transients ("...sufficiently small cooling rate, q "...), so that $J(T)$ represents an approximation valid for slow cooling rates. That is, in

other words, $J(T)$ in the form due to Volmer [3], and others, was derived for steady-state isothermal processes. This does raise questions about whether this theory can be used directly to predict supercooled droplet freezing in rapidly accelerating and cooling ducted spray flow fields. Clearly, future research on the freezing of very rapidly cooled water droplets is needed.

Stoyanova, et al., present $A(T)$ as

$$A(T) = Z f N_a \quad (73)$$

where

$Z \equiv$ the Zeldovich factor

$f \equiv$ the frequency of attachment of water molecules to the molecular cluster or ice germ

$N_a \equiv$ "the concentration of active centers on which nuclei can be formed"

The Zeldovich factor, Z , was then given as

$$Z = (W^*/3\pi kT n^{*2})^{1/2} \quad (74)$$

where

$n^* \equiv$ "the number of molecules in the nucleus"

Stoyanova, et al., give f as

$$f = n_s^* \beta kT / \eta v_m \quad (75)$$

where

$n_s^* \equiv$ "the number of attachment sites of molecules on the nucleus surface,"

$\eta \equiv$ "the viscosity of the liquid around the nucleus,"

$v_m \equiv$ "the molecular volume," i.e. the volume of a single molecule,

β \equiv is a factor that accounts for the change in liquid viscosity near the surface of the molecular cluster ($\beta \leq 1$).

The expression for $A(T)$ that then results is

$$A(T) = \left(\frac{Z n_s^* \beta k T}{\eta v_m} \right) N_a. \quad (76)$$

Stoyanova, et al., report that classical nucleation theory gives

$$W^* = \alpha \sigma_{ef}^3 v_m^2 / \Delta\mu^2 \quad (77)$$

and

$$n^* = 2W^* / \Delta\mu \quad (78)$$

where

α \equiv "a numerical shape factor for the molecular cluster, e.g., $\alpha = 16\pi/3$ for spherical nuclei,"

σ_{ef} \equiv the specific (effective) surface free energy of the liquid/nucleus interface (equivalent to σ_{sl} or σ_{ls} used in other $J(T)$ or $I(T)$ expressions presented herein).

$\Delta\mu$ \equiv the difference between the chemical potentials of the molecules in the liquid and in the ice germ or molecular cluster.

The authors note that, for heterogeneous nucleation, the value of σ_{ef} is less than that for homogeneous nucleation. So that, in general, one can write

$$\sigma_{ef}^3 = \Phi \sigma^3 \quad (79)$$

where

σ \equiv the specific surface free energy for homogeneous nucleation (same as σ_{ls}).

Φ \equiv $0 \leq \Phi \leq 1$; a parameter used for quantitative characterization of the nucleation activity of aerosol particles or "active centers."

Stoyanova, et al., note that “different theoretical models give different expressions for Φ .” Thus, theoretical models such as that discussed by, for example, Fletcher [24] can be used to estimate Φ for the application of $J(T)$ to predict heterogeneous nucleation freezing of supercooled water drops. Stoyanova, et al., report a functional form for Φ in the case where a hemispherical cap shaped nucleus, or ice germ, begins to form on a flat surface:

$$\Phi(\theta) = \frac{(2 + \cos \theta)(1 - \cos \theta)^2}{4} \quad (80)$$

This expression is attributed to Volmer [50]. In this expression for Φ , θ is the angle of “wetting” of the surface by the nucleus. Values of $\Phi(\theta)$ would be

$$\Phi(180) = 1$$

for either non-wetting or homogeneous nucleation;

$$\Phi(90) = 0.5$$

for “half-wetting” and;

$$\Phi(0) = 0$$

at “full wetting.” Full wetting would seem to imply particle freezing at the bulk water freezing temperature, $T = 273.16\text{K}$.

Stoyanova, et al., also provide thermodynamic expressions for the evaluation of $\Delta\mu$. For the freezing of water, they provide

$$\Delta\mu = \frac{\Delta S_m T \Delta T}{T_m} \quad (81)$$

where

$\Delta S_m \equiv$ the entropy change of melting (see equation (21), for example),

$\Delta T \equiv T_m - T$, the degree of supercooling experienced by the water sample,

$T_m \equiv$ the melting temperature of ice, $T_m = 273.16\text{K}$.

By combining the various expressions given so far, Stoyanova, et al., write $J(T)$ as

$$J(T) = Z n_s^* \beta \left(\frac{kT}{\eta v_m} \right) N_a \exp \left\{ \frac{-\alpha \sigma_{ef}^3 v_m^2 T_m^2}{\Delta S_m^2 k T^3 \Delta T^2} \right\} \quad (82)$$

where, with $\sigma_{ef}^3 = \Phi \sigma^3$, $J(T)$ will apply to both heterogeneous and homogeneous nucleation freezing events. For values of some of the parameters in the equation for $J(T)$, the authors provide:

$$\alpha = 16\pi/3$$

$$\sigma = 0.02 \text{ J/m}^2 \text{ (or } 20 \text{ erg/cm}^2\text{)}$$

$$\Delta S_m = 2.65 k \text{ (} k \text{ is Boltzmann's constant)}$$

$$v_m = 3 \times 10^{-23} \text{ cm}^3$$

An expression for the viscosity of liquid water was reported as

$$\eta(T) = 0.139 \left(\frac{T}{225} - 1 \right)^{-1.64} \text{ poise} \quad (83)$$

but, in the temperature range of their experiments, the authors used

$$\eta = 0.005 \text{ poise (constant } \eta\text{)}.$$

The authors note that analysis of the heterogeneous water sample freezing data that they had obtained then required a value of β of about 10^6 . Recall that, for Stoyanova, et al., β is the factor that accounts for "the change in liquid viscosity very near to the nucleus or ice germ surface." The small value for β may "actually reflect the commonly observed failure of the classical nucleation theory to give absolute magnitudes correctly." These aspects of the formulation of $J(T)$, due to Volmer [50], Walton [51], and others, as presented by Stoyanova, et

al., [36], as well as the extension of the theory to higher cooling rates of particles, need further review and clarification.

An application of the nucleation theory was made by Stoyanova, et al., to both seeded and unseed supercooled water freezing. The purpose was to evaluate key parameters of the theory, such as σ_p , Φ , θ , $\Delta\mu$, and W^* for both "seeded" and "unseeded" water samples. The "unseeded" water was not pure enough to reflect homogeneous nucleation, being referred to as "distilled water." Stoyanova, et al., provided tabulated values for the various parameters listed above that resulted from analysis of supercooled water sample freezing due to different types and amounts or concentrations of "atmospheric aerosol particles." As expected, σ_p , Φ , θ , $\Delta\mu$, and W^* all decrease as the concentrations of seed particles in the water samples increased. There were also changes in these variables for different types of seed particles or "active centers" as they were denoted.

In summary, Stoyanova, et al., like Fletcher [24], describe a general approach for the application of homogeneous nucleation theory to heterogeneous nucleation freezing processes. It is clear that atmospheric samples of water collected from flight through icing conditions will be needed in the future to begin the process of modeling freezing of atmospheric supercooled water, as well as for the simulation of icing tests in ground test facilities. The particle concentrations in these samples, as well as classification of particulate types will be needed for future computer-based modeling studies of the freezing of supercooled water. Water droplets that impinge on aircraft surfaces can form thin run off sheets whose small thickness may permit the use of modified homogeneous nucleation theory, or heterogeneous nucleation theory, to identify where in the run back process freezing begins. Other effects on the heterogeneous nucleation freezing process in supercooled water, such as the effect of different types of seed/mote particles simultaneously present in the water samples, as well as their concentrations, were also discussed

Stoyanova, et al., which makes their paper an excellent starting point for future researchers to review the theory.

2.14 Summary of the Overview

This section of the report was intended to provide a brief overview of some aspects of homogeneous nucleation theory applied to predict the nucleation or crystallization of supercooled liquid water droplets. This overview was not intended to be an inclusive survey of nucleation theory and it is not. It was also the purpose of this section to indicate how homogeneous nucleation theory has been extended to apply to heterogeneous nucleation events, that is, to instances where supercooled liquid water droplets, of ordinary purity, freeze due to contact with solid surfaces or to the presence of entrained foreign particles ("motes") in the water.

Because heterogeneous nucleation is the predominate mechanism by which supercooled water drops freeze in natural and artificial icing environments, the use of modified homogeneous nucleation theory to predict droplet freezing represents a physics-based freezing theory, compared to probability-based freezing theories developed earlier by Levine [11], Bigg [16,17], and applied by the present author to predict spray cloud freezing in ground test simulations of icing conditions [1,2]. The first-generation freezing model was based on the Levine-Bigg probability arguments for activities of the "freezing nuclei" in mote-induced freezing. The second-generation freezing model is based on modified homogeneous nucleation theory (MHNT) which can, in principle, account for the effects of mote-types on water particle freezing by accounting for the "wetting" characteristics of the mote-types, as well as for chemical additives that change either vapor pressures or interfacial surface free energies, and for surface geometries.

In the following sections, the development of a water particle crystallization model for heterogeneous freezing is described. The incorporation of this model into a numerical, one-dimensional, multiphase flow code is discussed and results are presented which were obtained from predictions made of water particle freezing in ducted flows using this code. Comparisons of these predictions are made to the same cases and similar results obtained with the first-generation water particle freezing model (the Levine-Bigg Model) [1,2].

Conclusions are drawn from the comparison of results and recommendations are made for further research and development of water droplet crystallization models for multi-dimensional numerical flow codes. The other implications of modified homogeneous nucleation theory are discussed, which include other aspects of adverse weather phenomena, as well as for weather simulation in ground test facilities.

3.0 BEHAVIOR OF THE FREEZING NUCLEI RATE OF CREATION FUNCTION, $J(T)$

3.1 $J(T)$ Utilized in Present Study

The first step taken by the present author to understand the behavior of the function $J(T)$ in predicting the onset of freezing of submillimeter, pure, supercooled water droplets was to reproduce the freezing temperature versus droplet diameter curve shown in Figure 54, page 496, of the paper of Langham and Mason [23]. This curve was based on their equation (4) of their paper which is provided as equation (43) of the present report (which corrects the typographical error in their equation (4)). The author presented the freezing temperature curve thus obtained, in Figure 1, of a previous report [1], as described in [1].

In the present study, the author found it convenient to use a simplified version of equation (43), which is the form first provided by Mason [14], shown in the present report as equation (36), page 11. The reason for using the simpler format for the equation is that by numerical

experimentation, it is obvious that the parameters having the greatest effect on the value of $J(T)$ are σ_{SL} , L_f and T . For given values of L_f and T , the function $J(T)$ is very sensitive to values of σ_{SL} , because its cube enters the exponential term of $J(T)$. Therefore, adopting a constant value for L_f , the heat of melting of ice as

$$L_f = 3.33 \times 10^5 \text{ J/kg},$$

and a shape factor ω evaluated at

$$\omega = 23$$

the form of the $J(T)$ equation used in the present study is given by

$$J(T) = 6.9708 \times 10^{38} T \exp \left\{ -\frac{2390.2}{T} - \frac{2.367 \times 10^7}{T} \sigma_{SL}^3 \left(\frac{273.16}{273.16 - T} \right)^2 \right\}. \quad (84)$$

3.2 Properties and Behavior of $J(T)$

The form of $J(T)$ given in equation (84) explicitly includes σ_{SL} as a free parameter meaning that σ_{SL} must be determined for both homogeneous as well as heterogeneous (nucleus-induced) freezing processes which are to be modeled in the present study. In the form given by equation (84), assuming, as did Langham and Mason [23], that 1 micron diameter pure water drops freeze in 0.6 seconds at -41°C , the value for σ_{SL} was found to be required at

$$\sigma_{SL}^* = 0.0212 \text{ J/M}^2 \quad (85)$$

Figure 1 shows a plot based on $J(T)$ of the calculated number of critical-sized active freezing nuclei for a one-micron diameter droplet of pure water as a function of the droplet temperature (in degrees centigrade). It was assumed, in the present study, that as a minimum, at least one freezing nuclei had to be present in the drop to initiate freezing at -41°C . The number of critical-sized nuclei present was evaluated from equation (51) and (52) of the present study, using $J(T)$ given by equation (84), under the assumption that each value of N_c obtained was obtained for a

fixed particle size (1 μ) and at each fixed temperature, T . Thus, under these conditions, equation (52) reduced to

$$N_c = J(T) * \frac{\pi}{6} D^3 * t \quad (86)$$

where $D = 1$ micron, and $t = 0.6$ seconds. Note, that, the actual production rate term for nuclei generation, that is, $J(T)$, has a distribution with temperature as shown in Figure 2. Thus, the use of the thermodynamic theory of spontaneous nucleation to predict particle freezing cannot be simply based on values taken by $J(T)$, but rather, must be obtained with $J(T)$ using some criteria such as that expressed by equations (51) and (52) in the present study. As a second point of interest, Figure 3 is provided to show the freezing nuclei production rate term $J(T)$ normalized by the number of molecules per cubic meter present in the water sample, N . Thus, Figure 3 shows a plot of $J(T)/N$ versus the temperature of the supercooled water. As this figure shows, the formation of molecular clusters containing between 20-300 molecules, that form the ice germs or ice precursors, is still a fairly rare molecular process in the water sample, even at -41°C .

3.3 Review of Dorsch and Hacker Data for Heterogeneous Freezing of Submillimeter Drops

In [1], the present author selected the data provided by Dorsch and Hacker [10] to obtain a Levine-Bigg type heterogeneous freezing function for use in a one-dimensional multiphase flow code. The Levine-Bigg freezing function fit to the Dorsch and Hacker data was

$$T_f = 422.2 + 5.592 \ln(D)R \quad (87)$$

where T_f is assumed to be the median freezing temperature of drops of diameter, D , in microns.

In degrees centigrade, this function was

$$T_f = -38.6 + 3.11 \ln(D)C. \quad (88)$$

The Dorsch and Hacker data set was also selected in the present study for consistency with the previous study [1] and for the reasons it was selected in the first study, as well as because this data set falls in the range typical of heterogeneous freezing experiments. The first step taken in the present study to develop a more physics-based particle freezing function for heterogeneous freezing, based on modified homogeneous nucleation theory, was to review the Dorsch-Hacker data set. Figure 4 shows a set of data plotted that came from Fig. 8 and part of Table I of the Dorsch-Hacker report [10]. The figure shows both the original, hemispherical "drop" sizes, as well as the equivalent spherical droplet sizes, D_{eq} , where

$$D_{eq} = 2^{-1/3} D \quad (89)$$

In the present study, additional data points were assembled from Table I, Fig. 8, Fig. 10, and Fig. 11 of the Dorsch-Hacker report which were then combined into a single figure, Fig. 5, of the present report. Also on Fig. 5 is a curve representing the data utilized in [1] to obtain the Levine-Bigg curve fit, equations (87) and (88). Thus, the previously used representation of the Dorsch-Hacker data in [1] was deemed adequate, for defining a Levine-Bigg freezing function. Figure 6 shows the data of Fig. 5 corrected to spherical diameters. In the present study, using all of the data of Fig. 6 to obtain a new representation of a Levine-Bigg freezing function, a new curvefit equation was obtained for particle heterogeneous freezing temperature, given by

$$T_F = -38.3 + 3.19 \ln(D) \text{ in degrees C} \quad (90)$$

This function is plotted in Fig. 7, and is essentially the same as that obtained previously [1], i.e., it compares favorably to equation (88).

Therefore, either of the Levine-Bigg type representations of the Dorsch-Hacker data are assumed accurate enough for expressing freezing behavior of the Dorsch-Hacker experiments on heterogeneous particle freezing.

The Levine-Bigg type of freezing function for heterogeneous freezing of water particles is considered to be a first-order or lowest-level freezing model from the standpoint of the physics of the process.

3.4 Freezing Function Based on Modified Homogeneous Nucleation Theory (MHNT)

A second order, or higher-level freezing model, was developed next in the present study based on the following criterion and equations:

- (1) Criterion for initiation of freezing of a water particle;

with the number of active freezing nuclei being given by

$$N_c(T, D, t) = \int_{t_o}^t J(T, D, t) V(D, t) dt \quad (91)$$

the freezing criterion is

$$N_c(T, D, t_F) = 1.0 \quad (92)$$

That is, in the present study, it is assumed that at least one active freezing nuclei must be created in the drop of volume, V , in the time period τ , where $\tau = t_F - t_o$, to initiate freezing. The times are defined herein as

t_o = the time when the droplet temperature first reaches the bulk water freezing temperature, i.e. 273.16 K

t_F = the time when the drop begins to freeze, i.e., by definition, when $N_c = 1.0$

- (2) It is assumed that the homogeneous nucleation rate function, $J(T)$, can be used, as modified, for heterogeneous freezing predictions. That is, the freezing nuclei rate equation,

$J(T, D, t)$, is the same function as the homogeneous nucleation rate equations given by equation (84), except, that σ_{SL} is now a function of drop diameter; that is, $\sigma_{SL} = \sigma_{SL}(D)$. Thus, $J(T, D, t)$ for heterogeneous freezing is assumed given by

$$J(T, D, t) = 6.9708 \times 10^{38} T \exp \left\{ -\frac{2390.2}{T} - \frac{2.367 \times 10^7}{T} [\sigma_{SL}(D)]^3 \left(\frac{273.16}{273.16 - T} \right)^2 \right\} \quad (93)$$

(3) It is assumed that the specific surface free energy for heterogeneous freezing is a function of drop volume, hence a function of the number and type of active freezing nuclei present in the droplet volume. For simplicity, at present, therefore, it was assumed that σ_{SL} could be represented by a smooth function of the droplet diameter, D , or,

$$\sigma_{SL} = \sigma_{SL}(D) \quad (\text{heterogeneous freezing})$$

From a practical standpoint, therefore, the specific surface free energy, $\sigma_{SL}(D)$, for the heterogeneous nuclei (water plus mote) responsible for the initiation of droplet freezing in the Dorsch-Hacker experiments can be determined for representative drop sizes by matching the criterion given by equation (92) for each drop size, at its median freezing temperature. To implement this process, and to develop a smoothly varying σ_{SL} function of D , the median freezing temperature of each size drop was assumed to be given by equation (90). Thus, $\sigma_{SL}(D)$ was determined by requiring $N_c(T_{Fi}, D_i, t_{Fi})$ to be unity for a selected set of freezing temperatures predicted by equation (90). Thus, if T_{Fi} is the median freezing temperature of droplet with diameter, D_i , then

$$N_c(T_{Fi}, D_i, t_{Fi}) = 1.0 = \int_{t_{oi}}^{t_{Fi}} J(T_{Fi}, D_i, t) V(D_i, t) dt \quad (94)$$

T_{Fi} and $V(D_i, t)$ were assumed constant during an assumed freezing interval given by

$$\tau_i = t_{Fi} - t_{oi} = 1.0 \text{ second.}$$

Then $N_c(D_p, T_{Fi})$ could be approximated by

$$N_c(T_{Fi}, D_i) = 1.0 = J(T_{Fi}, D_i) V(D_i) (1.0) \quad (95)$$

With

$$V(D_i) = \frac{\pi}{6} D_i^3 \quad (96)$$

the freezing criterion actually applied to determine $\sigma_{SL}(D_i)$ was

$$N_c(T_{Fi}, D_i) = 1.0 = J(T_{Fi}, D_i) \frac{\pi}{6} D_i^3 \quad (97)$$

Figure 8 shows $N_c(T_{Fi}, D_i)$ plotted as a function of T for drop sizes ranging from 1-10000 microns. The line $N_c = 1.0$ cuts each N_c curve at the median freezing temperature of that respective droplet size. For example, for the 5 micron droplet, the line $N_c = 1.0$ cuts the 5 micron N_c curve where $T = -33^\circ\text{C}$. By inspection of Fig. 7, it can be seen that this corresponds to the point on the curve fit for the heterogeneous, spontaneous (median) freezing temperature where 5 micron droplets freeze at $T_f = -33^\circ\text{C}$ (the ordinate value of T_f for $\ln(5) = 1.609$).

Each curve plotted on Fig. 8 was obtained by trial and error evaluation of σ_{SL} , changing the value of σ_{SL} for each drop size, until the N_c curve generated for that drop size passed through the appropriate freezing temperature when $N_c = 1.0$.

With the determination of each successful value of σ_{SL} , for each a priori chosen drop size, the data in Fig. 9 was constructed. Shown in Fig. 9 are two curve fits for σ_{SL} that were obtained by the same method to deduce the variation of σ_{SL} for heterogeneous freezing. The first attempt produced the distribution denoted $\sigma_{SL1}(D)$. A second attempt to create a σ_{SL} distribution in the present study corresponds, in Fig. 8, to the curve $\sigma_{SL2}(D)$. The differences between σ_{SL1} and σ_{SL2} result from a later, more thorough reconstruction and analysis of the Dorsch-Hacker data by the author. The forms of the curvefit equations for σ_{SL1} and σ_{SL2} are

$$\sigma_{SL1}(D) = 0.02045 - 0.00044528 \times (\ln(D)) - 7.2527 \times 10^{-5} (\ln(D))^2 \quad (98)$$

and

$$\sigma_{SL2} = 0.020228 - 0.00044755 \times (\ln(D)) - 7.9081 \times 10^{-5} \times (\ln(D))^2 \quad (99)$$

These two representations for σ_{SL} were kept in the present study to investigate the sensitivity of the predicted freezing behavior to variations in the values of σ_{SL} , for the same water sample data set. σ_{SL2} is the recommended curvefit because it is believed more accurate.

The differences in predicted submillimeter water particle freezing behavior in ducted flow when computed using the Levine-Bigg theory, σ_{SL1} , and σ_{SL2} , will be shown in the next section.

4.0 ANALYSIS AND EVALUATION OF THE WATER PARTICLE FREEZING MODEL BASED ON MODIFIED HOMOGENEOUS NUCLEATION THEORY

4.1 Introduction to the Approach

Because of a lack of detailed data on the freezing of convected, submillimeter, supercooled water droplets in ducted flows, the analysis and evaluation of the new model for heterogeneous freezing must be based on comparing model results with model results. Therefore, the predicted results of a calculation of water particle freezing in a ducted flow, made based on the Levine-Bigg freezing model [1], will be compared to the corresponding results obtained based on the modified homogeneous nucleation theory (MHNT) presented in the last section. The results obtained with the Levine-Bigg model were made with a one-dimensional, multiphase flow code described in references 52, 53 and modified and updated in the study reported in [1]. The flow code solves the fully-coupled mass, energy, and momentum conservation equations for a dilute, multiphase flow of water particles entrained in a ducted

airflow [52, 53]. The solution procedure is a Runge-Kutta fifth-order numerical integration scheme [54, 55] that requires a set of input duct flow initial conditions as well as the duct geometry.

The code was denoted, in the author's first report on water particle modeling [1], as the "AEDC1DMP" code (pg. 34, [1]). This code designation will be retained in the present study, meaning AEDC one-dimensional, multiphase flow code. It will be made clear when the results of this code refer to predictions made based on the Levine-Bigg (LB) type freezing model or the modified homogenous nucleation theory (MHNT) model for particulate freezing.

4.2 Implementation of the Particle Freezing Model

4.2.1 Freezing Criterion

In implementing the MHNT model in AEDC1DMP, the transformation of the calculation of the time integral for $N_c(T, D, t)$ to an integral along the flow with respect to the axial flow coordinate, was done as follows. The time integral was rewritten as

$$N_c(T, D, x) = \int_{x_0}^x \frac{J(T, D, x) V(D, x) dx}{U(x)} \quad (100)$$

where

$$dx = U(x) dt \quad (101)$$

and $U(x)$ is the particle velocity at x . The lower limit on the integral, x_0 , is the axial location in the flow where the given sized droplet first reaches (or cools down to) a temperature of 32°F (0 C or 273.16 K). Thus, droplet temperatures are monitored and when a given size drop temperature reaches 32°F, the evaluation of the integral is begun. However, the integral was actually implemented in the code by a running, finite summation

$$N_c(T, D, x_k) = \sum_i^k \frac{J^* V^* dx_i}{U^*} \quad (102)$$

where J^* , V^* , and U^* are mean or representative values of J , V , and U over the spatial integration step interval, dx_i , at the axial location, x_i , given by

$$x = x_k = x_o + \sum_i^k dx_i \quad (103)$$

The integration step intervals, dx_i , are controlled by the numerical integration scheme to control numerical (truncation) errors. Note, that when x reaches a limiting, input preset value, x_{max} , then the AEDC1DMP code terminates the calculation (integration) process for the entire flow.

The implementation of the Levine-Bigg type freezing function in AEDC1DMP was discussed previously [1,2]. However, to review the process, the implementation was as follows. In the course of computing the flow, the temperatures of the liquid drops are monitored. When a drop of diameter D cools to a temperature at or below the corresponding median freezing temperature T_{L_f} , for that drop size, the droplet is considered to have begun the freezing process, that is, the freezing procedure is initiated.

4.2.2 Model of the Freezing Process

Whether the initiation of freezing is triggered by a criterion given by the Levine-Bigg model or by the modified homogeneous nucleation theory (MHNT) model, once freezing has been initiated, the computation of the drop freezing is the same. The steps are

- (1) the supercooled liquid drop is assumed to become, instantaneously, a slushball or mixture particle containing both liquid water and ice at the normal melting temperature of ice (492°R, 32°F, or 0°C).
- (2) The amount of the mixture particle that is ice is determined from an energy balance for the particle based on conditions just before freezing was initiated and just after freezing was initiated. Since the mixture temperature is assumed at 492°R, the only

free variable that can be determined from the energy balance is the fraction of liquid that remains after freezing is triggered, given by

$$\alpha_F = 1 - \frac{C_L}{H_F} (492 - T_{L_F}) \quad (104)$$

where

$\alpha_F \equiv$ mass fraction of drop or mixture particle that remains liquid at 492°R. (hence, $(1 - \alpha_F)$ of the particle has become ice at 492°R).

$C_L \equiv$ specific heat of liquid water

$H_F \equiv$ heat of fusion of liquid water

$T_{L_F} \equiv$ freezing temperature of the supercooled liquid water droplet.

Details of the energy balance are provided in [1].

- (3) The density of the mixture particle is now the mean density of a two-phase system wherein the phases cannot occupy the same volume. Hence, the mean density of the mixture particle is given by

$$\bar{\rho} = \frac{\rho_L \rho_I}{\alpha_F \rho_I + (1 - \alpha_F) \rho_L} \quad (105)$$

where

$\rho_L \equiv$ density of liquid water

$\rho_I \equiv$ density of ice

The specific heat of the particle is also redefined as a mass-average specific heat given by

$$\bar{C}_P = \alpha_F C_{P_L} + (1 - \alpha_F) C_{P_I} \quad (106)$$

where

C_{p_L} = specific heat of liquid water

C_{p_i} = specific heat of ice

- (4) The size of the mixture particle is then given by requiring that the total mass of the particle remains constant during the (assumed instantaneous) transition of the particle from supercooled liquid drop to a mixture particle of water and ice at 492°R. Thus,

$$\bar{\rho} \frac{\pi}{6} \bar{D}^3 = \rho_L \frac{\pi}{6} D_{L_f}^3 \quad (107)$$

or

$$\bar{D} = \left(\frac{\rho_L}{\bar{\rho}} \right)^{1/3} D_{L_f} \quad (108)$$

where

\bar{D} \equiv the new diameter of the mixture particle

D_{L_f} \equiv the diameter of the supercooled liquid drop just before freezing is initiated.

- (5) Thereafter, the mixture "drop" is treated as any other droplet in the flow. Heat, mass, and momentum exchanges with the air flow are computed in the same way as that for the all droplets. However, as each amount of heat is extracted from the particle, the amount of liquid remaining in the droplet is reduced (α_f is reduced), and a new mean density, and particle diameter are re-calculated. In the recalculation, the mass loss or gain of the particle by mass transfer is taken into account, as well as energy lost or gained by the mass transfer process. The amount of new ice formed is also calculated. The details of the mass and energy balance during freezing of the evaporating, two-phase particle are given in Appendix B.

When the entire particle has become ice, α_f reaches zero, and the particle is now completely frozen.

During the freezeout process for the mixture particle, the particle temperature is held constant at 492°R.

- (6) Once the particle completely freezes, its density becomes that of ice, as well as its specific heat. From this instant or location in the duct flow, the particle undergoes mass, energy, and momentum exchanges with the air flow as an ice particle. It can gain or loose mass by sublimation based on the partial pressure of ice and the air flow specific humidity.

5.0 EVALUATION OF AEDC1DMP CODE ON REPRESENTATIVE DUCT FLOW CASES

5.1 Baseline Case of Ducted, Two-Phase Flow

The base case computed for a comparison purpose was a ducted flow with a "single" water spray station at its inlet.

In the code AEDC1DMP, the water is assumed to enter the airflow at up to ten different injection stations that are separated, axially in the duct. Each injection station is capable of putting in a given amount of water, in a given sized water particle with its specified velocity and temperature. When all of the injection stations are bunched close together, axially, in the duct, they can be used to model a single spray station with a spray droplet size distribution characterized by ten discrete drop sizes. This was the approach taken in the previous study [1] to examine the freezing of two-phase, ducted flows representative of both full-scale and research-scale icing test facilities. Note, that to illustrate and emphasize the ducted-flow freezing processes of supercooled, submillimeter water particles, the air flow inlet total temperature utilized was significantly lower, at 460°R, than is typical of many icing tests, where an airflow inlet total temperature of 486°R is more likely. In any case, for consistency with previously

obtained results, the same airflow and water inlet conditions have been specified and are provided below.

Table 1. Duct Air Flow Inlet and Water Spray Conditions for Baseline Test Case 1

Air Inlet Conditions				
Total Pressure, psfa				1123.48
Total Temperature, °R				460°R
Velocity, ft/s				20
Mach Number				0.0189
Inlet Relative Humidity, percent				15.78
Water (Particle) Input Conditions				
Injection Station No. (ft)	Particle Diameter (microns)	Particle Temperature (°R)	Particle Velocity (ft/s)	Load Factor (FL)
1, 0.0	5	530	46	6.85 E-05
2, 0.01	10	530	46	2.06 E-04
3, 0.02	15	530	46	4.80 E-04
4, 0.03	20	530	46	3.62 E-04
5, 0.04	30	530	46	2.06 E-04
6, 0.05	40	530	46	3.43 E-05
7, 0.06	50	530	46	1.37 E-05
8, 0.07	60	530	46	1.37 E-06
9, 0.08	80	530	46	1.37 E-07
10, 0.09	100	530	46	1.4 E-08
			Total FL	= 1.37 E-03

FL = lbm of water/lbm of dry air injected at a given injection station

The duct geometry used for this reference or baseline case is shown in Fig. 10. As is clear from inspection of Fig. 10, and as discussed in [1], this duct geometry is not representative of full-scale icing test facilities. Rather, it was chosen in the earlier study [1] because it was related to a similar geometry of interest. For consistency in comparing results, therefore, this geometry was also retained in the present study.

5.2 Comparison of Predicted Results of Baseline Case for Three Particulate Freezing

Models

Figure 11 shows predicted temperatures of 10 micron water droplets, as they vary with axial distance along the flow, for three heterogeneous freezing models. The models utilized were the Levine-Bigg model, given specifically by equation (87), and the modified homogeneous nucleation theory (MHNT) using σ_{SL1} and σ_{SL2} for the specific surface free energy specifications.

As can be seen, the comparison is extremely good. The results obtained with the σ_{SL} function σ_{SL2} gives a closer agreement with the Levine-Bigg model than does σ_{SL1} . Since it is thought that σ_{SL2} was obtained from a more thorough data analysis than σ_{SL1} , the better agreement of the predicted results with σ_{SL2} is expected, although such good agreement in both quality and quantity displayed in Fig. 11 is remarkable.

On the basis of the results shown in Fig. 11, and found to be consistently the same for all droplet sizes, it was decided to utilize the function $\sigma_{SL2}(D)$ for the heterogeneous freezing model for all further calculations made in the present study.

Figure 12 shows a comparison of predicted droplet temperatures made with two versions of AEDC1DMP, one version with the Levine-Bigg (LB) freezing model implemented, and the other version with the modified homogeneous nucleation theory (MHNT) model implemented, based on σ_{SL2} . The agreement between the first (LB) and second order (MHNT) models is good. An interesting difference in the predicted results occurs for the 5 micron droplets. The Levine-Bigg model results in the 5 micron droplets freezing at the location in the duct flow where their temperature has reached about 427°R. (The freezing occurs so rapidly, it occurred between print step sizes in the program and is not shown, therefore, in the plot, Fig. 12.) The drops have shrunk, by evaporation, to about 2 micron in diameter at this location. On the other hand, the modified homogeneous nucleation theory model predicts that the 5 micron drops, shrunk to 2 micron, do not freeze within the domain of the calculation, because, even though the drops have reached a freezing temperature, their volume is too small to generate at least one active freezing nuclei. In other words, the criterion

$$N_c = \int JV dt = 1 \quad (109)$$

was not satisfied for these small drops throughout the calculated length of flow. Thus, significant potential differences could arise in predicted freezing behaviors made with a Levine-Bigg model and with a modified homogeneous nucleation theory model, for certain circumstances.

The predicted temperature distributions for all of the other drop sizes appear similar or comparable, based on the two different freezing models.

(The calculated temperature distributions shown in Fig. 12 also indicate that the particles took longer (more distance) to freeze for the MHNT model predictions, than in the Levine-Bigg model predictions, than in the Levine-Bigg model predictions. This was not due to any differences caused by the freezing models, but due to improvements made in AEDC1DMP to integrate the heat and mass transfer processes of the freezing particles in a more recent version of AEDC1DMP in which the MHNT model was implemented.)

Figure 13 shows a comparison of the predicted droplet sizes from AEDC1DMP with the MHNT model implemented, for the ten different drop sizes as they move along the flow. Drop freezing shows up in these curves by sudden small increases in drop size (a kink) in the curves. Clearly, the 5 micron particle curve does not show a sudden increase, indicating that the drop stays liquid along the entire flow.

5.3 Calculations of Flow in a Representative Icing Test Facility

5.3.1 Introduction

The duct geometry of baseline case calculated, with results shown in Figures 10-13 was not representative of full scale icing test facility duct geometries. Therefore, a second test case was prepared and calculated wherein the duct or wind tunnel geometry and scale represents typical icing research or icing test wind tunnel geometry.

The results from computations of test case 2 are shown below.

5.3.2 Nominal Test Conditions in a Full-Scale Icing Facility

The duct or wind tunnel geometry assumed for test case 2 is shown in Figure 14. This wind tunnel like configuration has a large inlet and a steep contraction section, to minimize flow disturbances. Icing spray nozzles are assumed to be put in the plane of the large inlet. The test section is located at $x = 46$ ft, so that the state of the water particles injected at the inlet of the wind tunnel should be in kinetic and thermal equilibrium with the air flow by the time they reach the test section. The tunnel has a large contraction ratio (inlet flow area divided by test section flow area), hence, the range of permissible inlet air flow velocities is small, ranging from near 0 to about 45 ft per second. At the higher inlet air velocities, the test section has reached near-choking, or sonic flow conditions. Generally, icing tests are conducted at air flow or flight-simulating speeds in the range of a few hundred miles per hour. Therefore, a nominal set of inlet test conditions was defined for the representative calculation made with AEDC1DMP. The nominal test conditions are listed below.

Table 2. Nominal Tunnel Inlet Test Conditions for Icing Wind Tunnel-Test Case 2

Air Inlet Conditions

Total Pressure, psfa	2074
Total Temperature, °R	500
Velocity, ft/s	20.8
Mach Number	0.0188
Relative Humidity, %	54.7

Water (Particle) Input Conditions

Injection Station No. (ft)	Particle Dia. (microns)	Particle Temperature (°R)	Particle Velocity (ft/s)	Load Factor (FL)
(a) 1 (0.0)	50	634	15.6	0.00018
(b) 1 (0.0)	500	634	15.6	0.00018

Note: The case was computed first (case 2a) with a single particle size of 50 microns to represent the spray cloud, then computed (case 2b) with a single particle size of 500 microns. In

each computation, the 50 or 500 micron particle represented the mean volumetric diameter of the spray cloud particle size distribution at the inlet.

Some selected results from computing these flow cases are shown in Figures 15-17. Figure 15 shows the gas velocity together with the velocities of a 50 micron particle and a 500 micron particle. The calculation shows that the larger particle did not reach velocity (kinetic) equilibrium with the air flow at the test section. On the other hand, the 50 micron particle did achieve a velocity equal to the gas velocity at the test section location.

Figure 16 shows similar results for the gas temperature and the temperatures of the two different sized particles. In the case of the 500 micron particle, its temperature is above the gas temperature by about 10 degrees, R, at the test section location due to thermal lag, however, the 50 micron particle temperature has fallen quickly, through evaporation and cooling, to its wet-bulb temperature about 5 degrees, R, below the gas temperature. The effects of air flow inlet humidity on droplet cooling and thermal non-equilibrium have been well-documented elsewhere, for example [53], and will not be discussed herein. However, it is possible to increase the inlet air flow humidity to increase the drop wet bulb temperature at the test section, to be equal to the gas temperature. Large droplet thermal lag effects could also be reduced, by reducing inlet humidity. Thus, opposite humidity modifications are required for large and small drops to account for thermal non-equilibrium effects at the test section.

Finally, Figure 17 shows the changes in the droplet diameters as the water particles pass down the duct. The changes in droplet diameter are greatest where the rate of evaporation is greatest, in the duct inlet throat region. (Note that kinks or slope discontinuities in the plotted curves are due to the data output frequency or axial spacing, not to discontinuities in computed results.)

Test Case 2, therefore, provided some nominal results which show how AEDC1DMP can be used for assessment of flow variations and flow quality typical of full-scale icing test or research wind tunnels. In this test case, neither the 50 micron drop nor the 500 micron drop were near their spontaneous (median) droplet freezing temperatures. The next test case computed will be one that represents a full-scale icing test with supercooled droplet freezing.

5.3.3 Test Conditions in a Full-Scale Icing Facility with Supercooled Droplet Freezing

By trial, computation, and output analysis, a set of wind tunnel inlet conditions was found that produced supercooled droplets, slushball or mixture particles, and ice particles in the test section located of the flow. The set of inlet conditions found is listed below in Table 3.

Table 3. Tunnel Inlet Test Conditions for Icing Wind Tunnel Flow with Water Particle Freezeout – Test Case 3

Air Inlet Conditions

Total Pressure, psfa	2076
Total Temperature, °R	475
Velocity, ft/s	40
Mach Number	0.037
Relative Humidity, %	26

Water (Particle) Input Conditions

Injection Station No. (ft)	Particle Dia. (microns)	Particle Temperature (°R)	Particle Velocity (ft/s)	Load Factor (FL)
1 (0.0)	5	495	16	9.06 E-06
2 (0.02)	10	495	16	2.73 E-05
3 (0.04)	15	495	16	6.35 E-05
4 (0.06)	20	495	16	4.79 E-05
5 (0.08)	30	495	16	2.73 E-05
6 (0.10)	40	495	16	4.54 E-06
7 (0.12)	50	495	16	1.31 E-06
8 (0.14)	60	495	16	1.81 E-07
9 (0.16)	80	495	16	1.8 E-08
10 (0.18)	100	495	16	2.0 E-09
Total FL				= 1.82 E-04

As the input data in Table 3 indicate, an inlet spray cloud with a 10 drop size distribution was input at the wind tunnel entrance station. The inlet air temperature and the water spray temperatures are rather low, the water being only slightly above freezing and the air at below freezing temperature (15°F). This combination of inlet conditions lead to predicted freezeout of some of the drop sizes in the wind tunnel flow at the test section station.

Figures 18 show some of the calculated results obtained with AEDC1DMP utilizing the modified homogeneous nucleation freezing model for predicting the freezing of supercooled water particles. Figure 18 shows the air flow Mach number distribution from duct entrance to the test section. Note that this case's inlet conditions lead to rather high test section Mach number, about 0.69. This is about twice the nominal or typical value for icing tests in full-scale facilities. The higher value of air flow Mach number ensured that air flow static temperatures would be low enough to induce particle freezeout, with a freezing model calibrated to the Dorsch-Hacker data set [10].

Figure 19 shows the predicted variations in drop or particle sizes from entrance to test section. Note that the initially 5 micron particle has disappeared, by evaporation, by about 4.5-5.0 feet from the duct entrance. This indicates that, for similar inlet conditions, a real water spray cloud with similar drop size distributions would experience all of the drops smaller than, say, 10 microns evaporating quickly in the inlet. The smallest surviving droplet at the test section would probably be in the range from 6-8 microns. These results, of course, depend on the inlet conditions, especially water injection temperature and inlet air flow humidity.

Figure 19 also shows size-jumps in the 15 to 80 micron particles which indicates that these water particles have begun to freezeout in the air flow where the size-jumps occur. The 10 and 100 micron droplets remain completely liquid at the test section.

Figure 20, which shows the predicted water particle or droplet temperatures, confirms that the 15-80 micron particles have begun to freeze in the flow. The (initially) 10 micron particle does not experience freezing, nor does the (initially) 100 micron particle, up to their arrival at the test section and, they have very different temperatures. The other particles have either become ice particles (15, 20, 30 micron particles) or are slushball or mixture particles (40, 50, 60, 80 micron particles) at the test section. The results of the calculation made with the MHNT freezing model indicate the potentially complex results that could be obtained in actual icing or adverse weather test simulations when either inlet flow, water spray nozzle, or duct geometry result in thermal and kinetic non-equilibrium flow conditions at the test station or test article.

Concluding the results of test case 3, Figure 21 shows the predicted water particle velocities. As Figure 21 shows, for this case, all of the particles, even the 100 micron droplet, are in, or very near to, kinetic or velocity equilibrium with the air flow at the test section ($x = 46$ feet).

Briefly summarizing this section, the AEDC1DMP code is capable of predicting results of two-phase, dilute, air and entrained water droplet flows in research scale and full-scale icing and adverse weather test facilities. The incorporation of a second generation or second order (in the hierarchy of physics of freezing modeling) modified homogeneous nucleation theory (MHNT) for particle freezing in AEDC1DMP gives the code the capability of accounting for particulate freezing over a wide range of flow conditions. Appendices C-E describe the data input audits format in detail, for user convenience. Included are the input data for test case 3. Appendix F lists a sample output from AEDC1DMP for test case 3.

6.0 DISCUSSION OF RESULTS OF STUDY, SUMMARY, CONCLUSIONS, AND

RECOMMENDATIONS

6.1 Summary of the Present Study

The study and the report had three parts. The first part was an examination of homogeneous nucleation theory and its modifications and applications to the prediction of the freezing of supercooled pure water particles and heterogeneous freezing of water particles containing motes or foreign substances. The second part addressed the behavior of the homogenous nucleation rate function, $J(T)$, as a function of water temperature. This function was then calibrated to a set of heterogeneous particle freezing data, provided by Dorsch and Hacker [10], by assuming that the surface specific free energy for an ice-water interface could be represented as a function of the volume or diameter of the particles containing the motes. With this functional form for the surface free energy in hand, the function $J(T)$ became, in essence, calibrated to the Dorsch-Hacker data set.

The third part of the study comprised some numerical computations of two-phase, dilute, air and entrained water particle flows, using a new version of the AEDC one-dimensional, multiphase flow code, AEDC1DMP. The results of these calculations demonstrated that modified homogeneous nucleation theory [MHNT] could be satisfactorily used in numerical flow models to identify the initiation of heterogeneous freezing events in submillimeter, supercooled water particles in the computed flows. The freezing model described in the report accounts for the effects of time, particle size, and particle temperature on the initiation of freezing.

6.2 Conclusions

The conclusions of the research reported herein are as follows:

- (a) Classical homogeneous nucleation theory can be easily modified to predict heterogeneous freezing of submillimeter, supercooled water particles.
- (b) Both empirical and theoretical methods can be used to account for the effect of foreign particles, surface wetting and dissolved chemicals in the initiation and formation of freezing events.
- (c) A particulate freezing model for heterogeneous freezing of submillimeter, supercooled water particles based on modified homogeneous nucleation theory has been incorporated in a one-dimensional, multiphase flow code (AEDC1DMP) with excellent results, and can easily be incorporated into multidimensional, multiphase flow codes.

6.3 Recommendations

The recommendations of the present study are as follows:

- (d) A multidimensional, multiphase flow analysis of water spray nozzle discharge plumes should be pursued with the highest priority. The analysis should include water particle freezing in the spray plumes to investigate the possibility of creating ice crystals in the spray plumes. This topic has been raised in the first part of this research program [1,2], and it is also seen as an important continuation of the present study.
- (e) The physics of water particle freezing should continue to be studied under heterogeneous freezing conditions. The further development of models for the specific surface free energy of the molecular clusters that trigger freezing events should be pursued. Models of σ_{sl} , such as that described by Volmer [50], Fletcher [24], Stoyanova [36], and others, should be developed so that the effects on particle

freezing of different kinds of motes in the atmospheric water particles, as well as in ground test facility water supplies, can begin to be addressed.

- (f) In view of the previous recommendation, it is further recommended that additional atmospheric data be obtained on the composition of water particles in nominal icing conditions. The data should include the chemical and physical composition of supercooled water particles or water samples. This includes dissolved and/or entrained chemicals, as well as the kinds, shapes, and numbers of solid particles in the atmospheric icing environment. Similar effort should be made to catalogue the same information for water used in ground test simulations of icing and adverse weather simulations for aircraft engines and/or their components.
- (g) Consideration of the freezing process for supercooled water should be extended to thin films of water on aircraft surfaces, including those on ice accretions. In other words, it should be investigated whether there are water run-back modes wherein thin films of supercooled water can be formed in the ice accretion process. If so, then the initiation of freezeout of run back water, under such conditions, might be predicted by a modified homogeneous nucleation theory.

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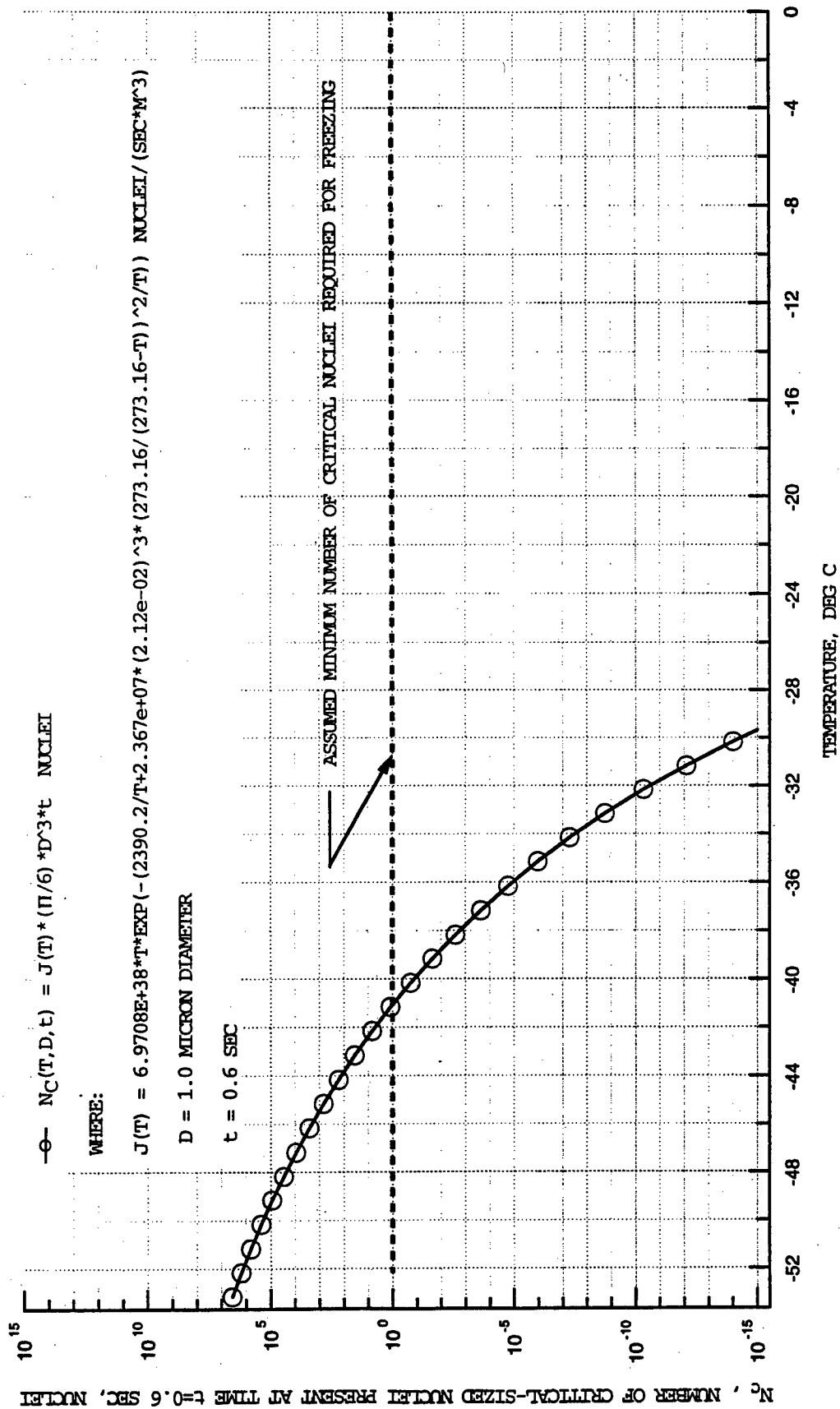


FIG.1 PLOT OF THE NUMBER OF CRITICAL-SIZED MOLECULAR CLUSTERS PRESENT IN A 1 MICRON DROP AFTER IT HAS EXISTED FOR $t = 0.6$ SECONDS, AT TEMPERATURE, T , UNDERGOING HOMOGENEOUS FREEZING

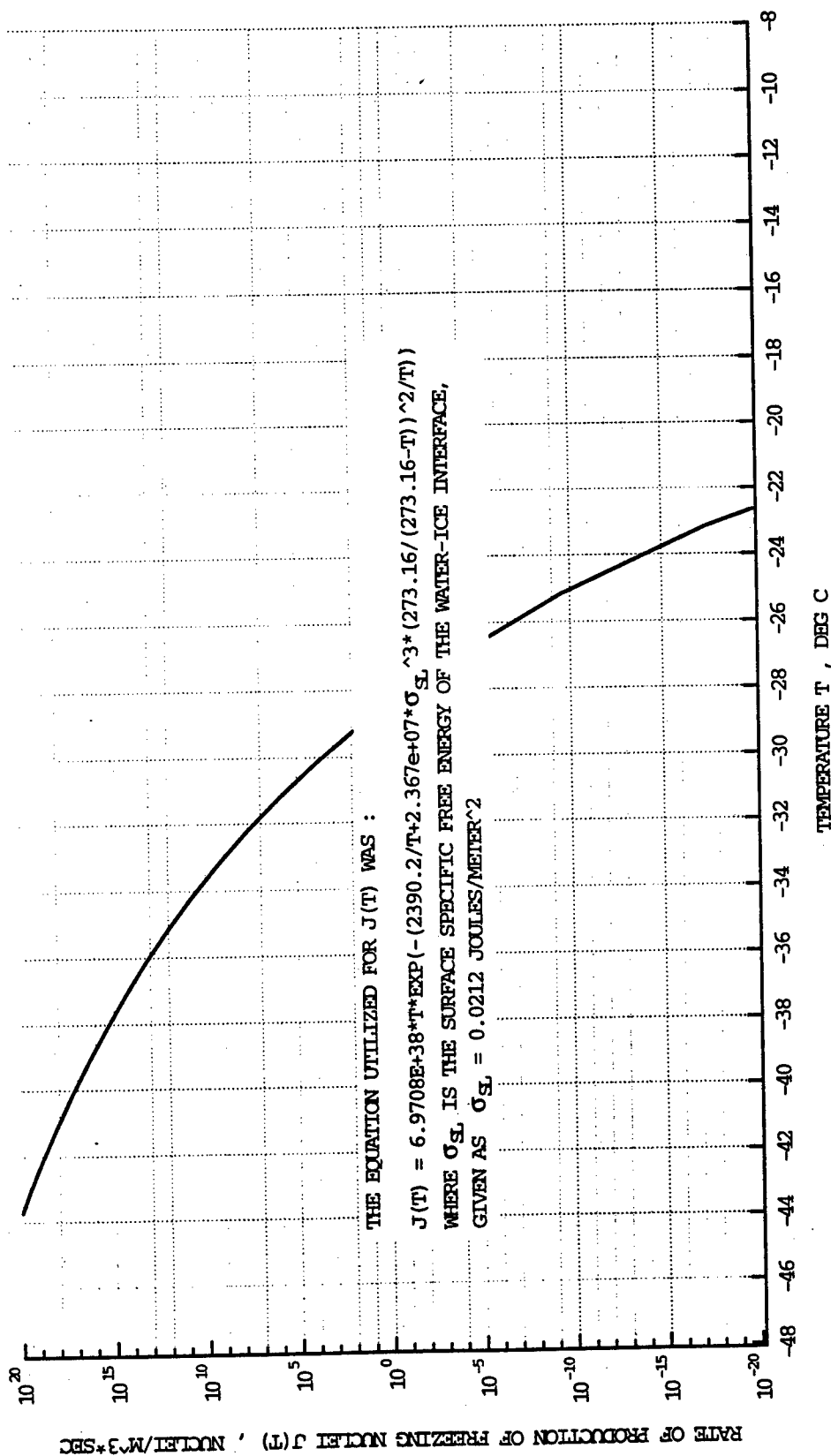


FIG.2 PLOT OF THE HOMOGENEOUS NUCLEATION RATE , $J(T)$, AS A FUNCTION OF WATER PARTICLE TEMPERATURE

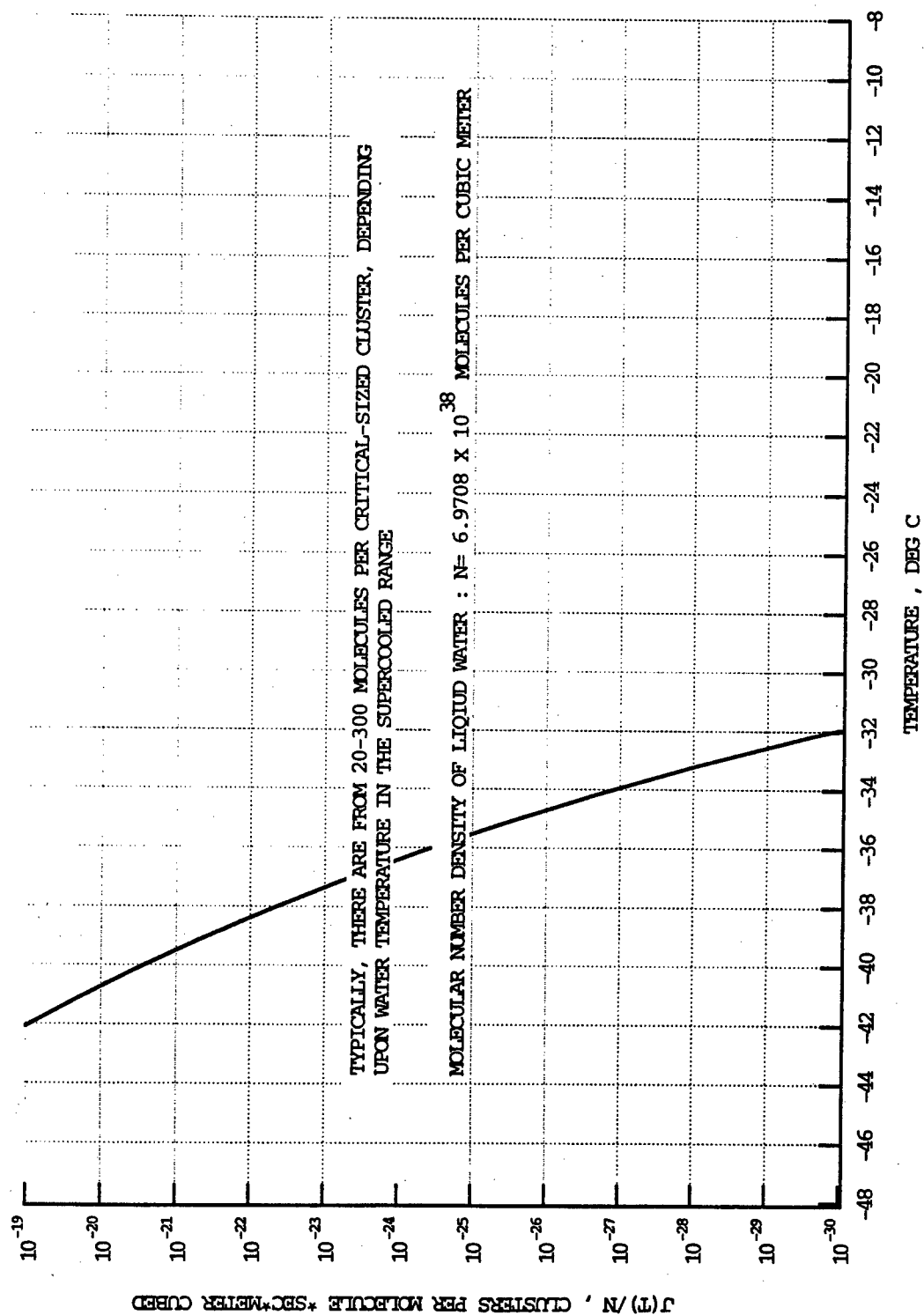


FIG. 3 PLOT OF THE NORMALIZED RATE OF CREATION OF CRITICAL-SIZED MOLECULAR CLUSTERS AS A FUNCTION OF THE WATER PARTICLE TEMPERATURE

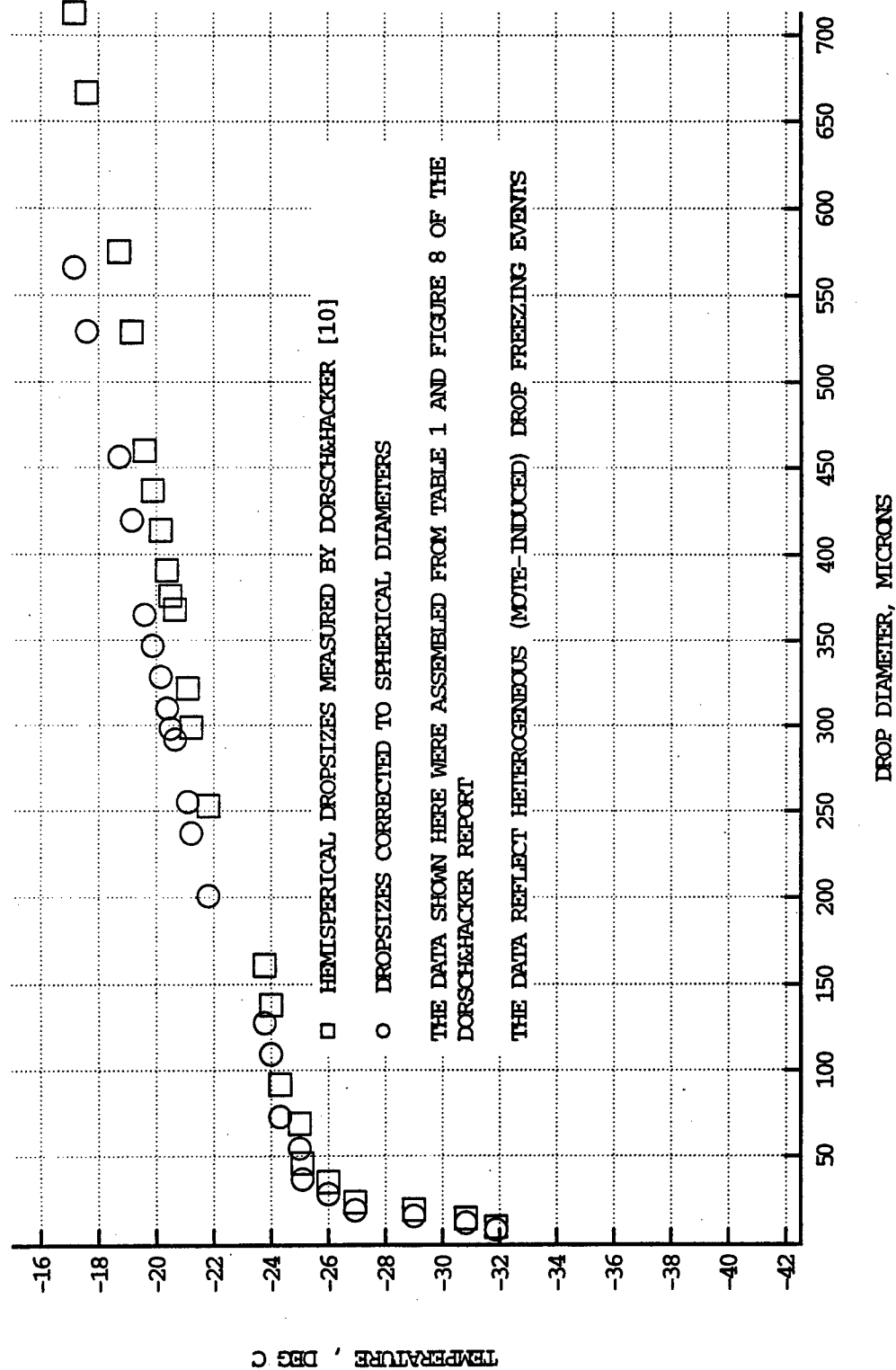


FIG. 4 PLOT OF "AVERAGE" OR MEDIAN, HEMISPHERICAL, SUPERCOOLED DROP SPONTANEOUS FREEZING TEMPERATURE AS A FUNCTION OF DROP DIAMETER, FROM THE DORSCH AND HACKER REPORT

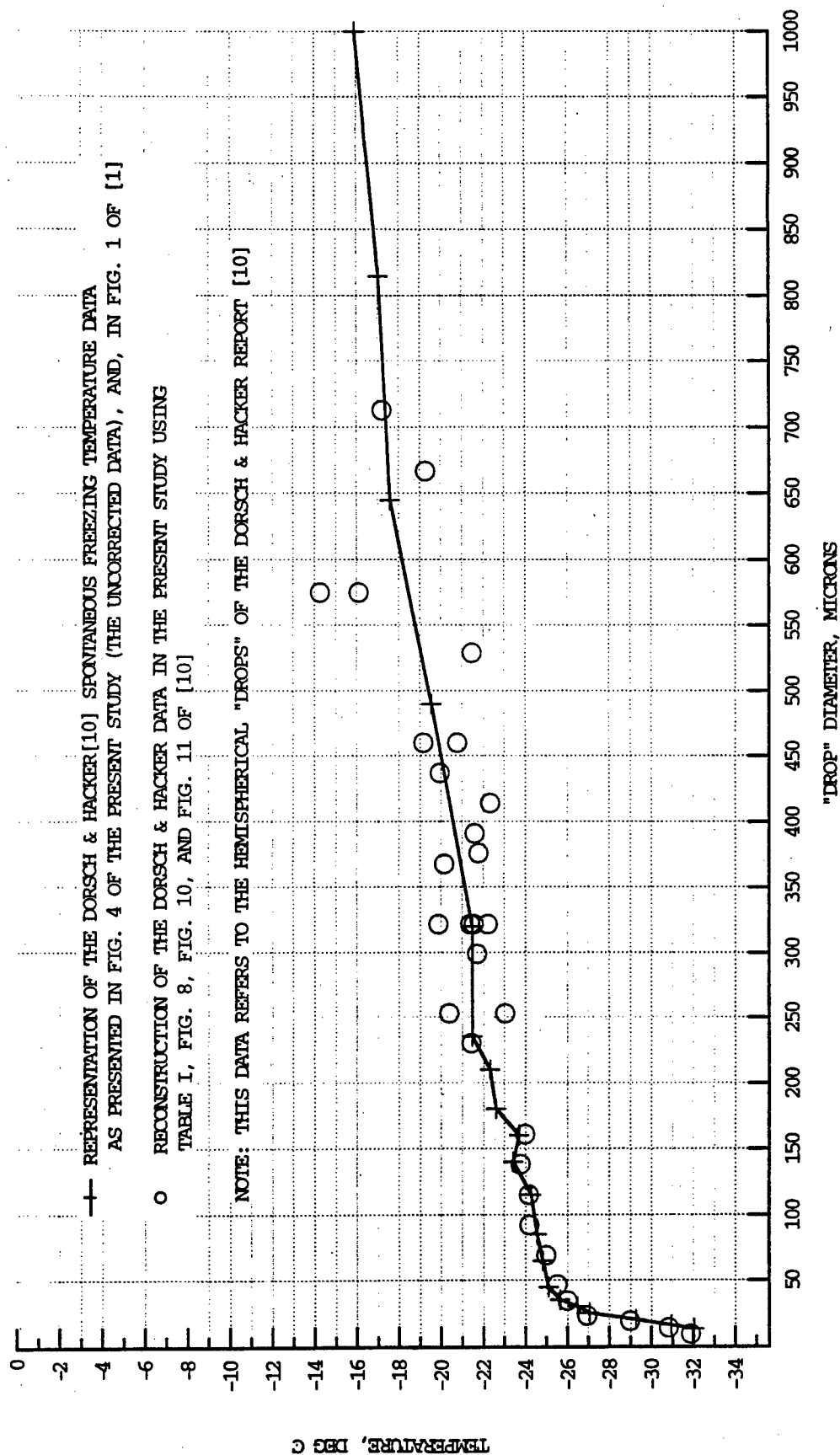


FIG. 5 REEXAMINATION OF THE DORSCH & HACKER "AVERAGE" SPONTANEOUS FREEZING TEMPERATURE DATA TO OBTAIN AN ACCEPTABLE LEVEL OF CONFIDENCE FOR MATCHING IT WITH MODIFIED HOMOGENEOUS FREEZING THEORY

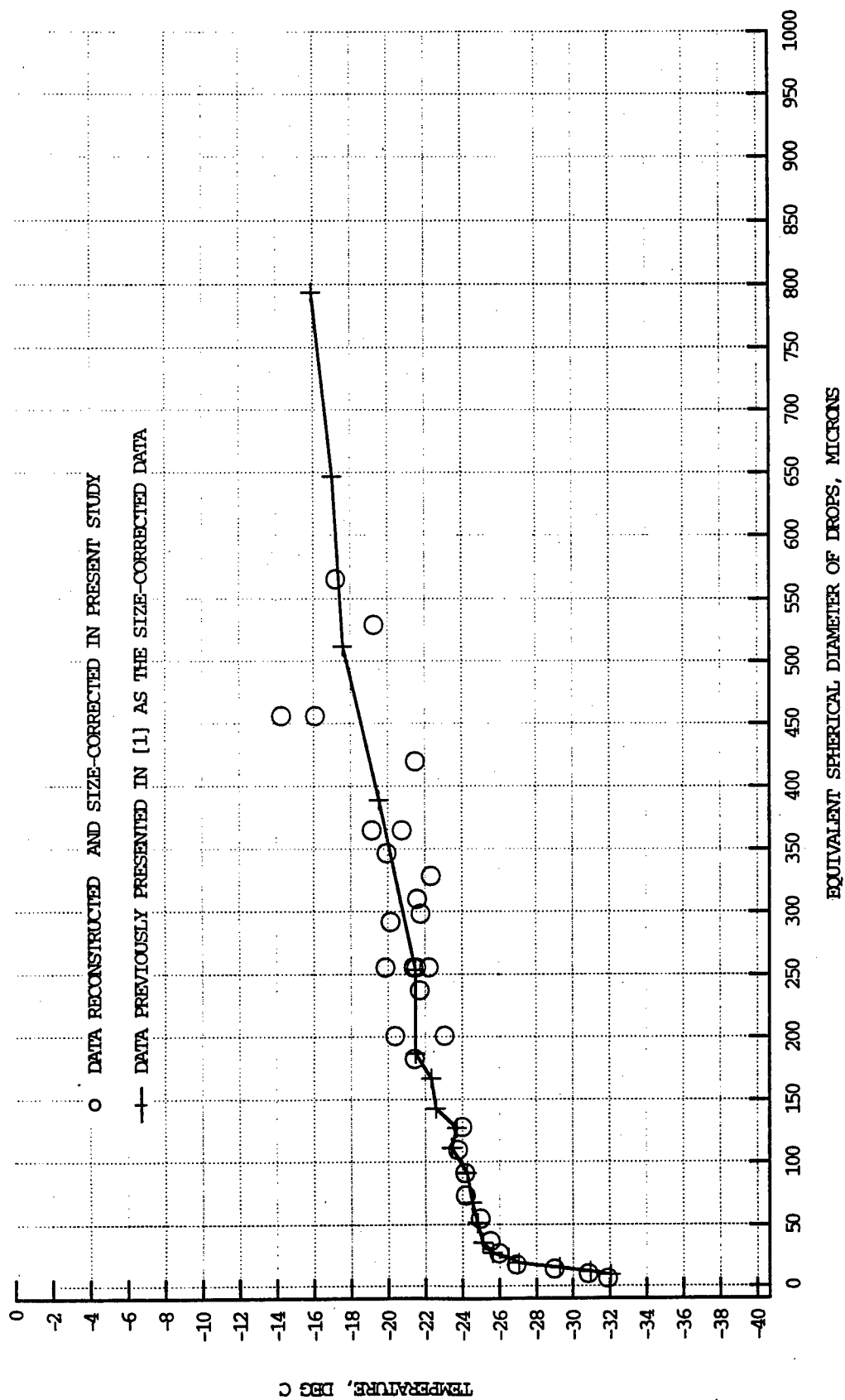


FIG. 6 DATA OF FIGURE 5 CORRECTED TO SPHERICAL SIZES

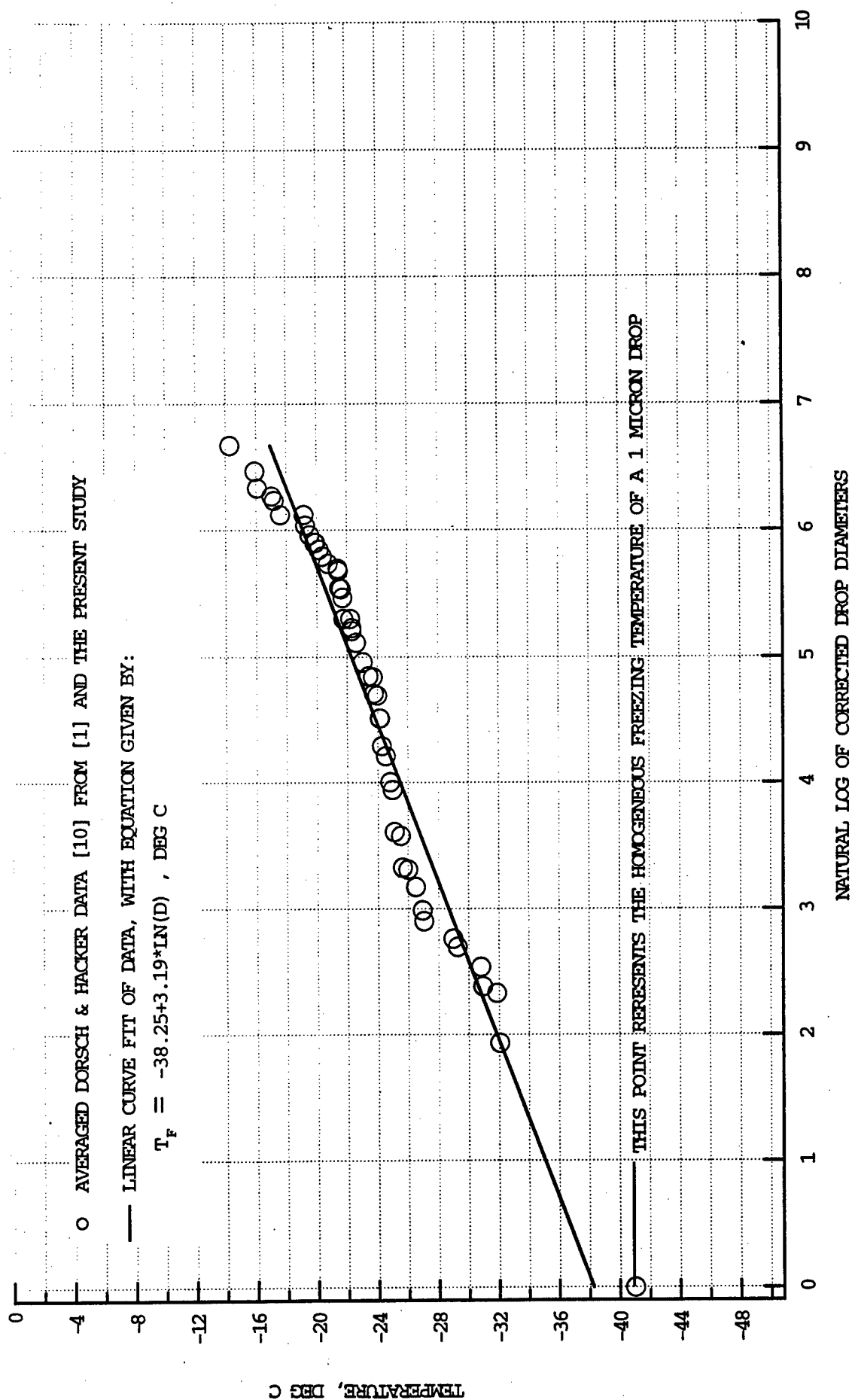


FIG. 7 PLOT SHOWING LINEAR FIT TO AVERAGED SPONTANEOUS FREEZING TEMPERATURES, T_F , OF THE DORSCH AND HACKER DATA [10], BASED ON CORRECTED DROP DIAMETERS

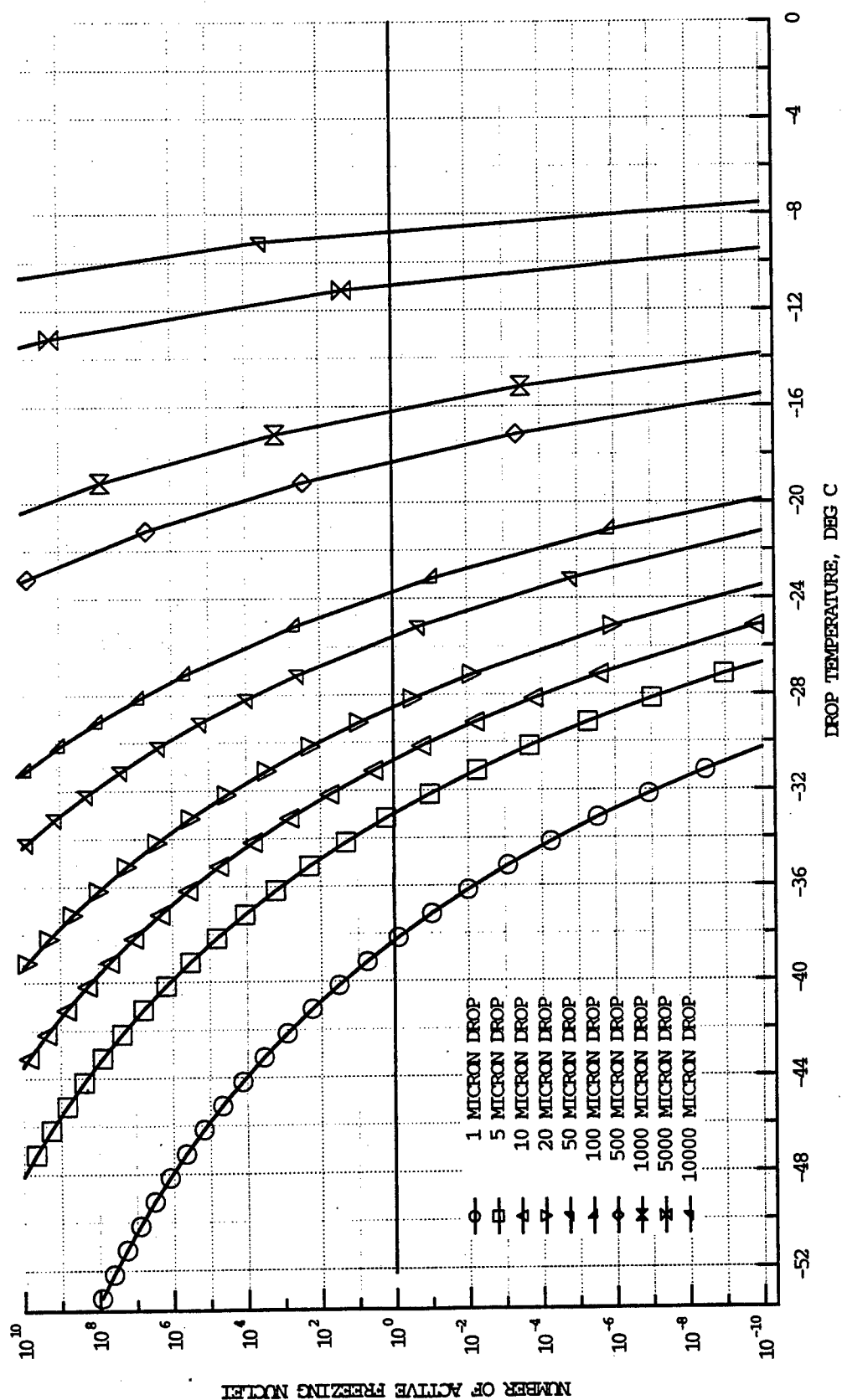


FIG. 8 PLOT OF THE PRODUCTS OF $J(T) \cdot \text{DROP VOLUME} \cdot \text{TIME}$, FOR DIFFERENT SIZED DROPS, USED TO MATCH THE DORSCH-HACKER MEDIAN FREEZING TEMPERATURES

TWO DIFFERENT ATTEMPTS TO OBTAIN THE BEST CURVE FITS OR EXPRESSIONS OF σ_{SL}

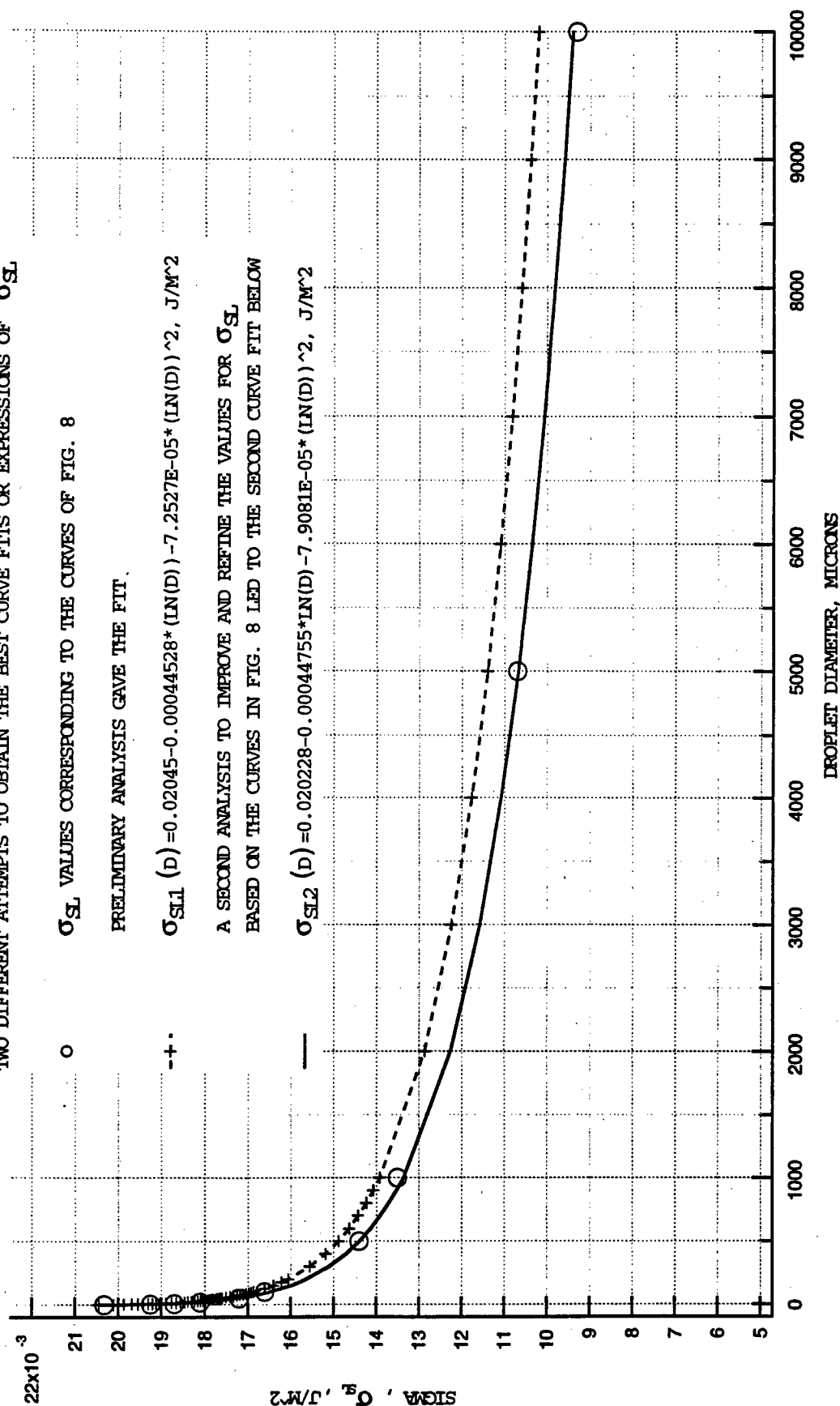


FIG. 9 CURVE FITS OF THE SPECIFIC SURFACE FREE ENERGY, σ_{SL} , OF AN ICE-WATER INTERFACE FOR HETEROGENEOUS NUCLEATION FREEZING, EVALUATED BASED ON THE DORSCH-HACKER DATA [10]

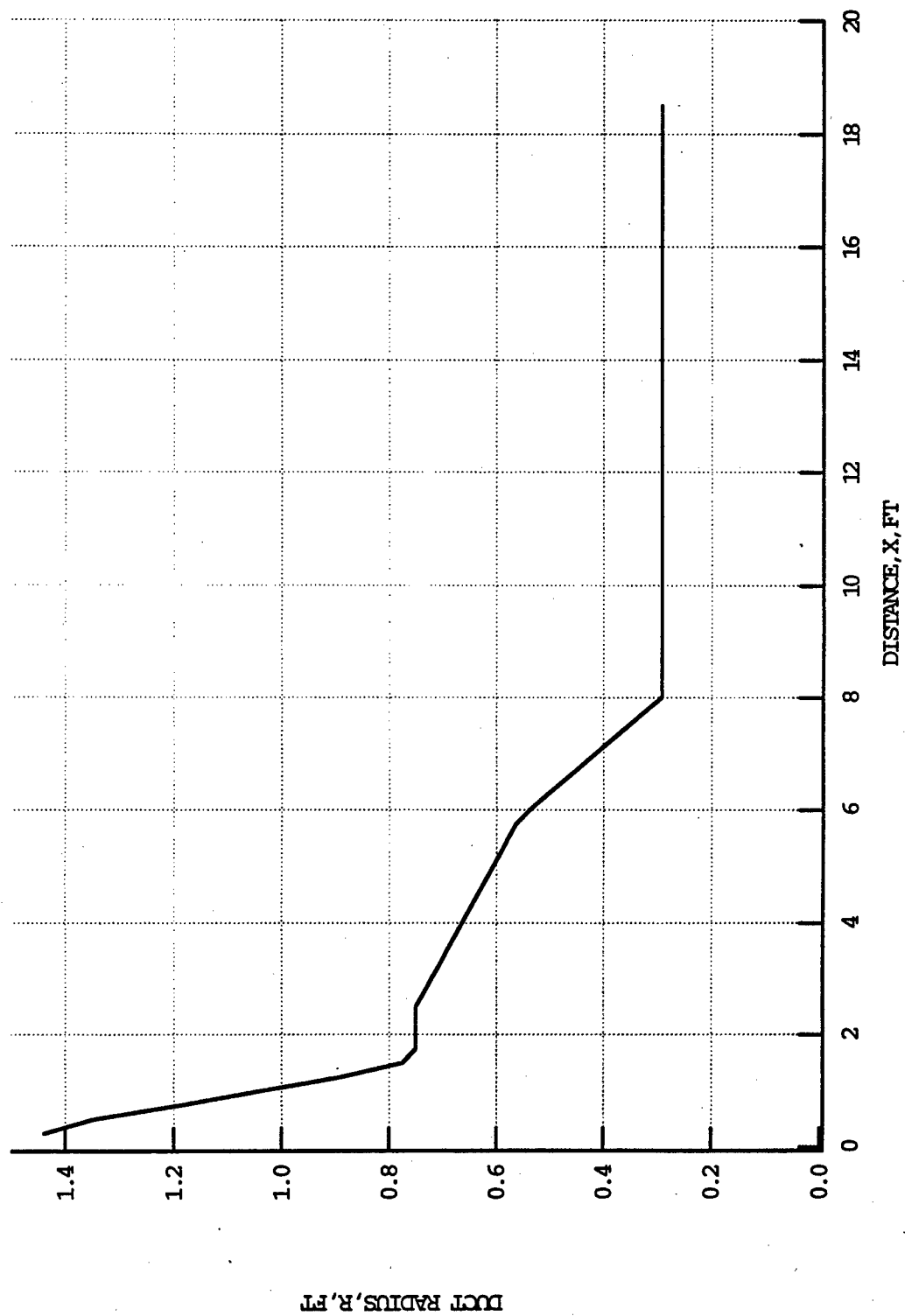


FIG. 10 DUCT GEOMETRY OF TEST CASE USED IN REFERENCE [1]

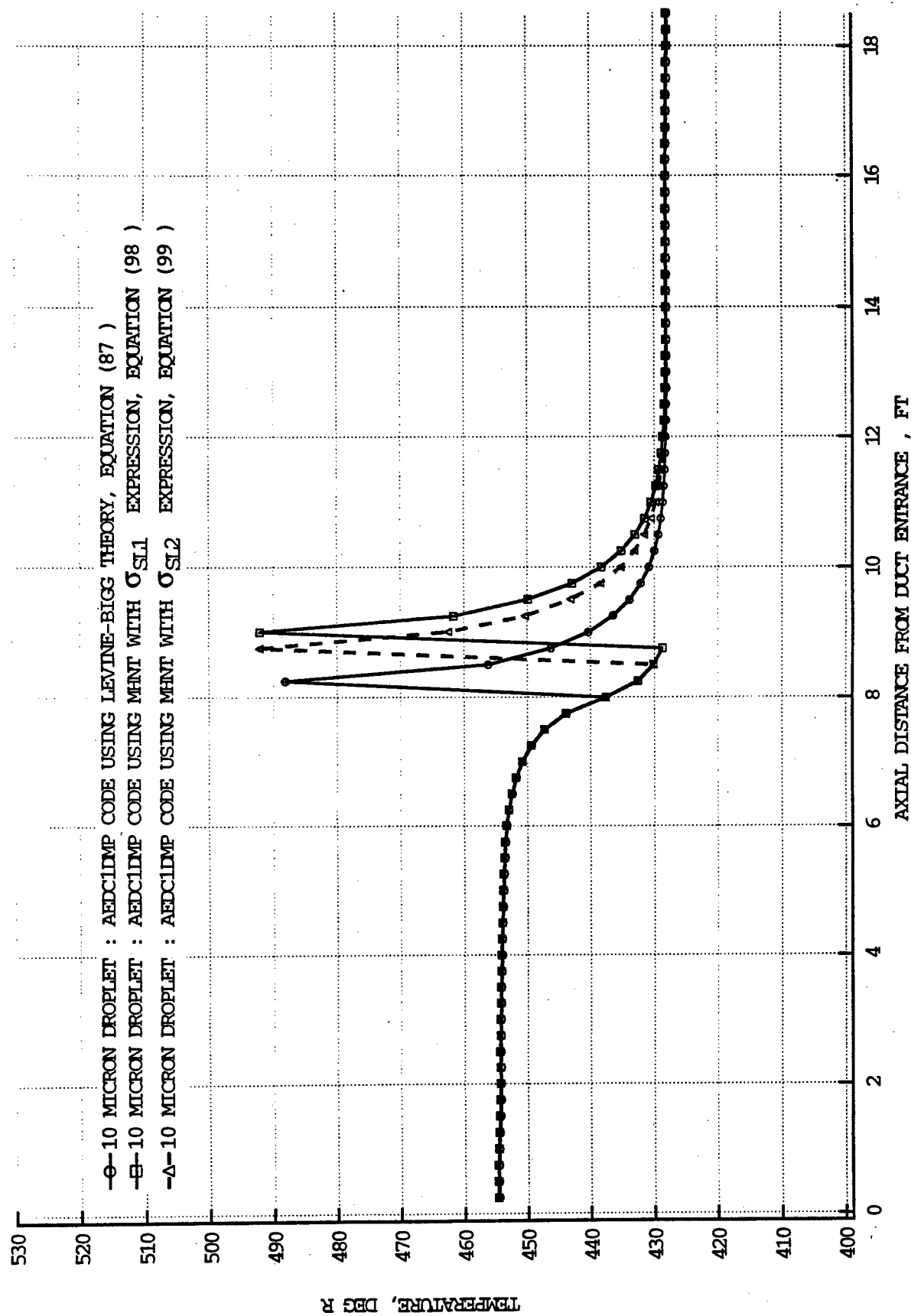


FIG. 11 COMPARISON OF CALCULATED DROPLET TEMPERATURE DISTRIBUTIONS IN DUCTED FLOW WITH FREEZING CONDITIONS PREDICTED

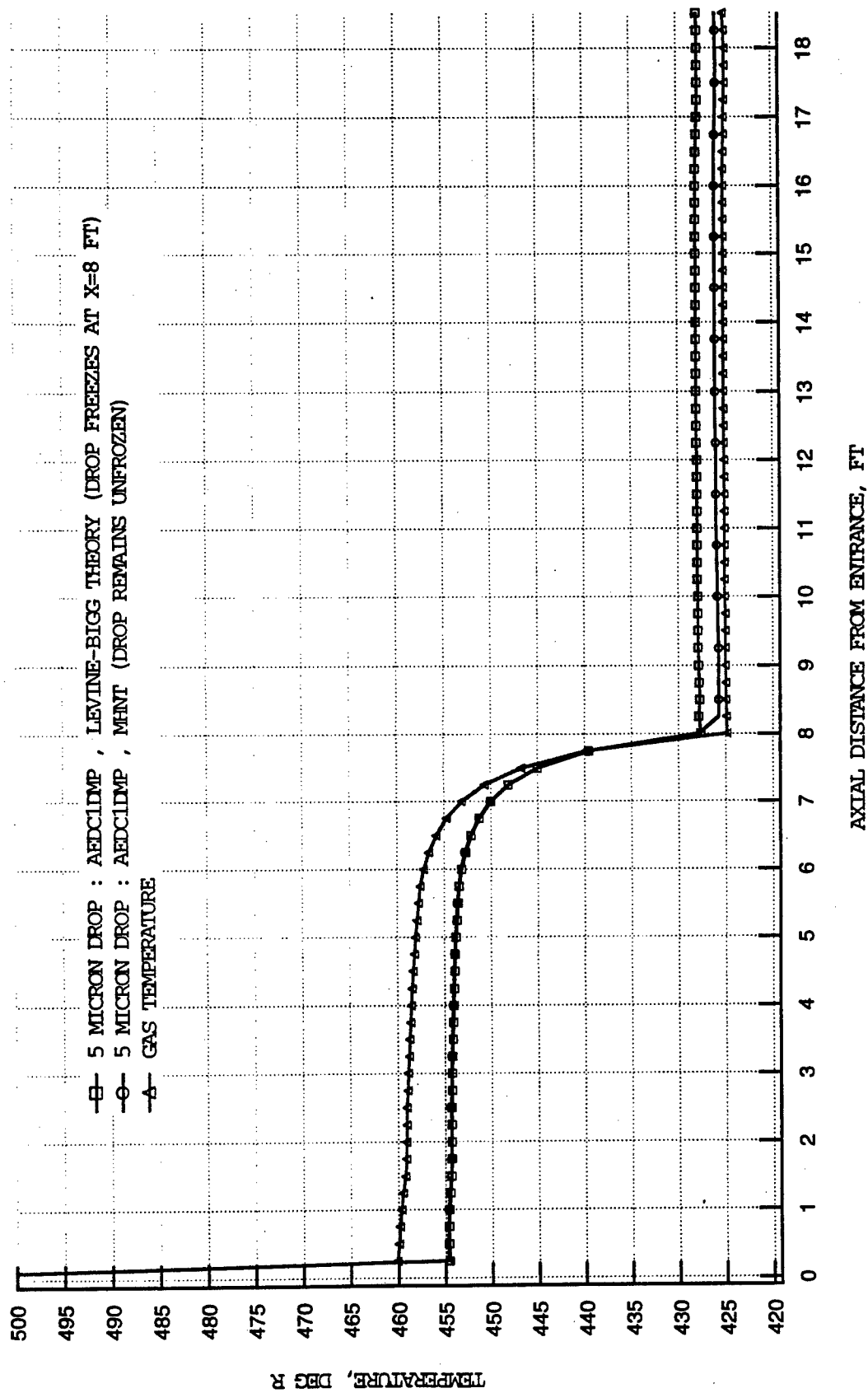


FIG. 12 COMPARISON OF PREDICTED PARTICLE TEMPERATURES DURING FREEZING: LEVINE-BIGG THEORY VS MODIFIED HOMOGENEOUS NUCLEATION THEORY (MINT)

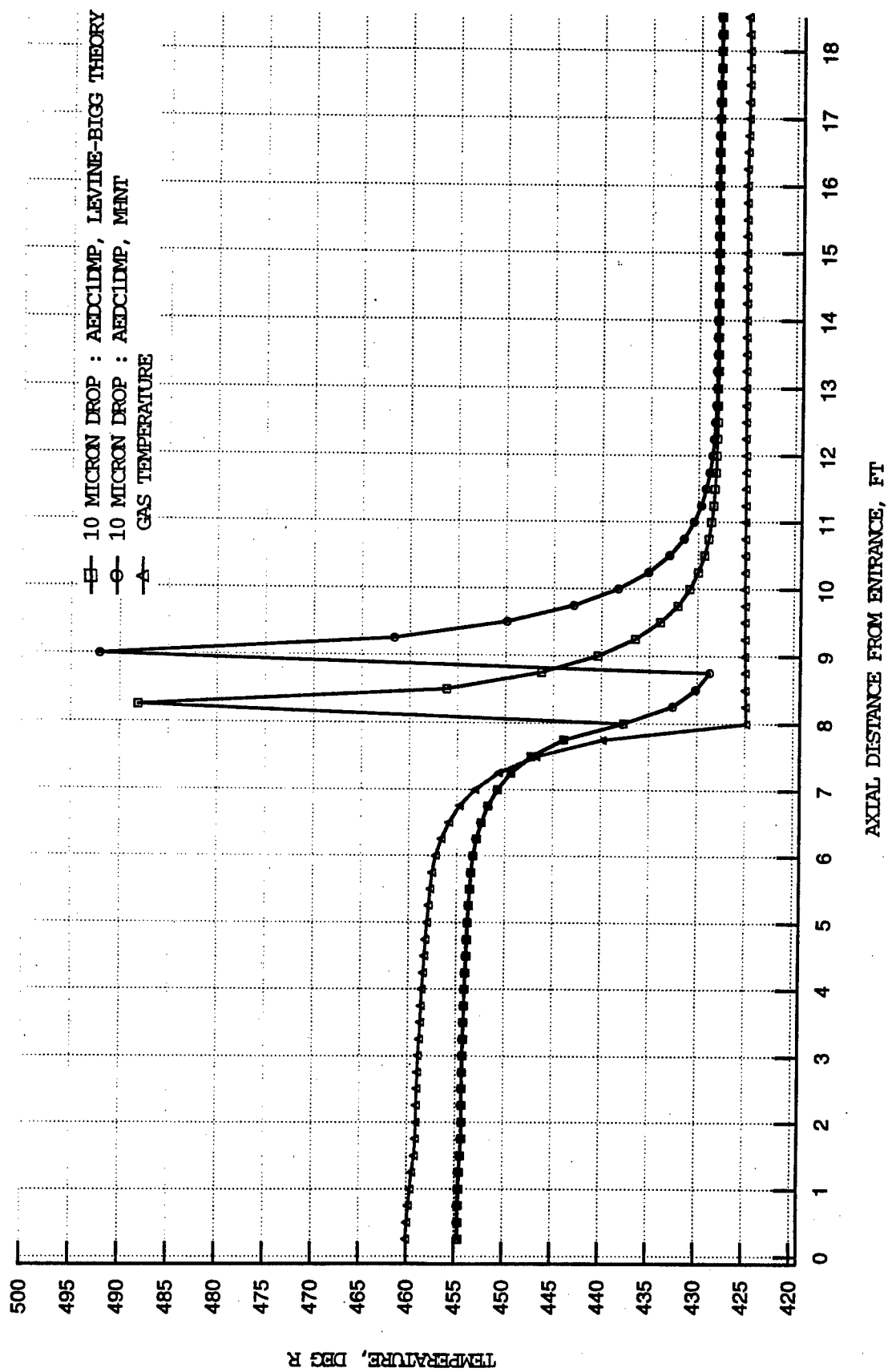


FIG. 12 (CONTINUED) COMPARISON OF PREDICTED PARTICLE TEMPERATURES DURING FREEZING: LEVINE-BIGG THEORY VS MODIFIED HOMOGENEOUS NUCLEATION THEORY (MENT)

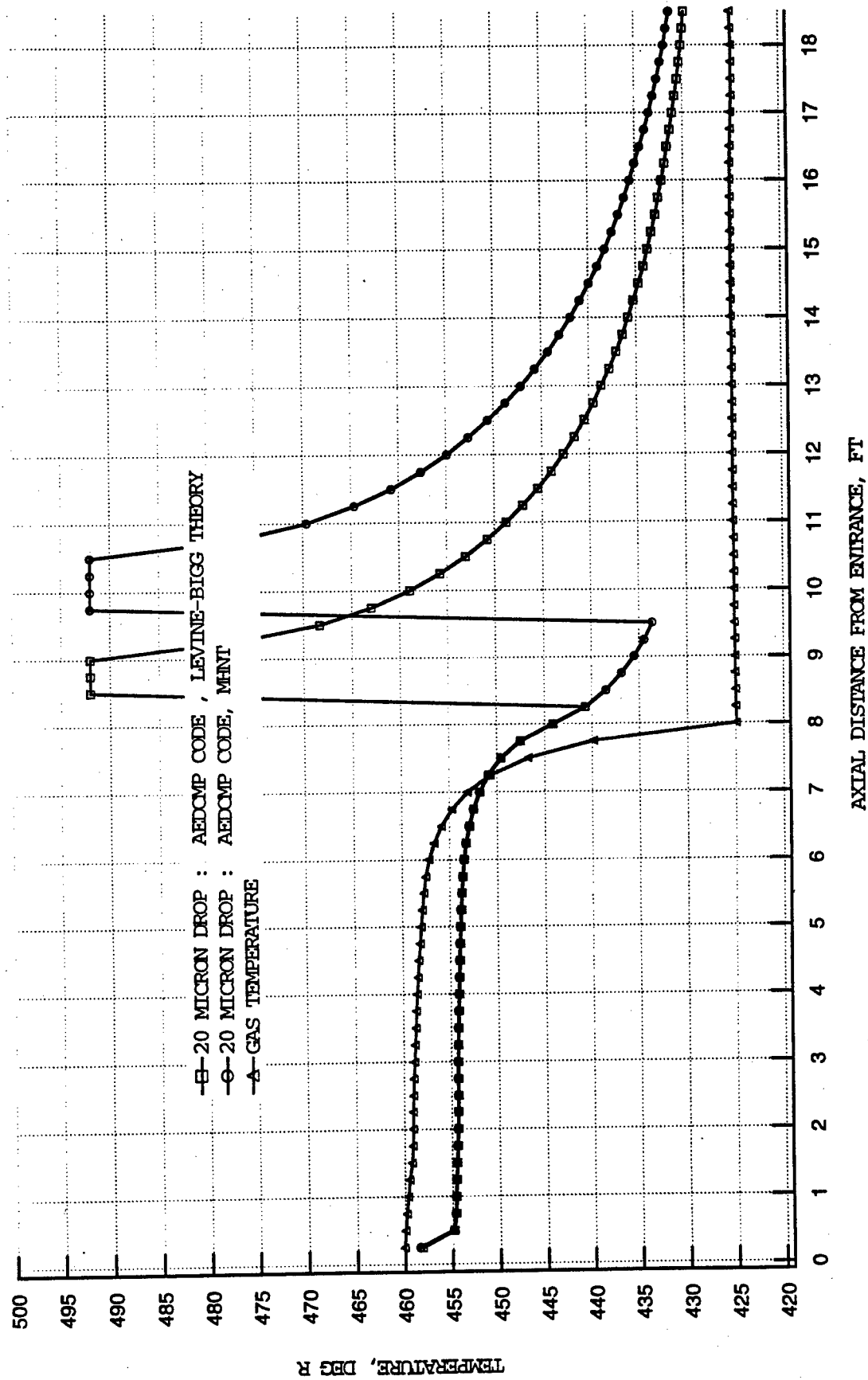


FIG. 12 (CONTINUED) COMPARISON OF PREDICTED PARTICLE TEMPERATURES DURING FREEZING: LEVINE-BIGG THEORY VS MODIFIED HOMOGENEOUS NUCLEATION THEORY (MHNT)

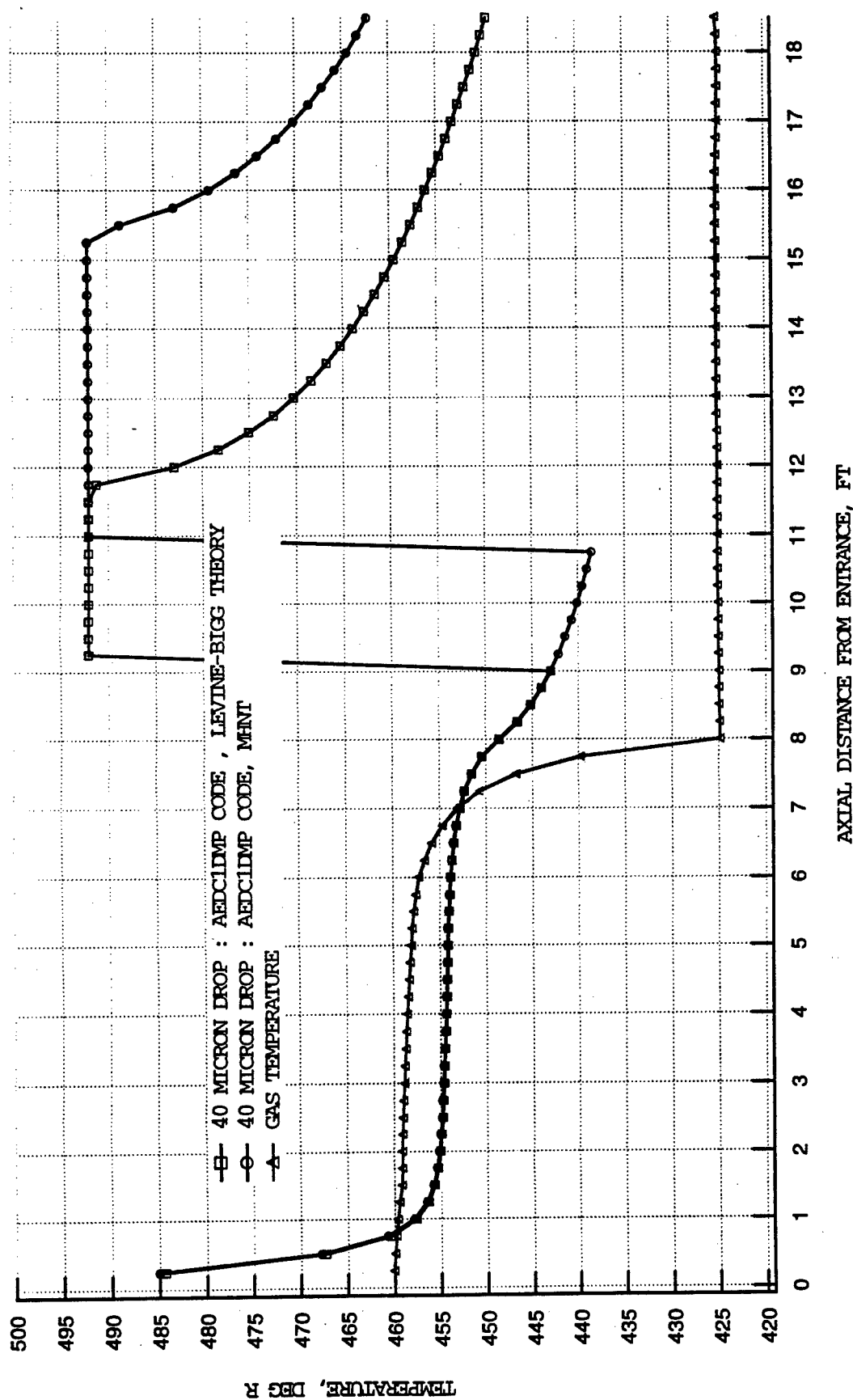


FIG. 12 (CONTINUED) COMPARISON OF PREDICTED PARTICLE TEMPERATURES DURING FREEZING: LEVINE-BIGG THEORY VS MODIFIED HOMOGENEOUS NUCLEATION THEORY (MNT)

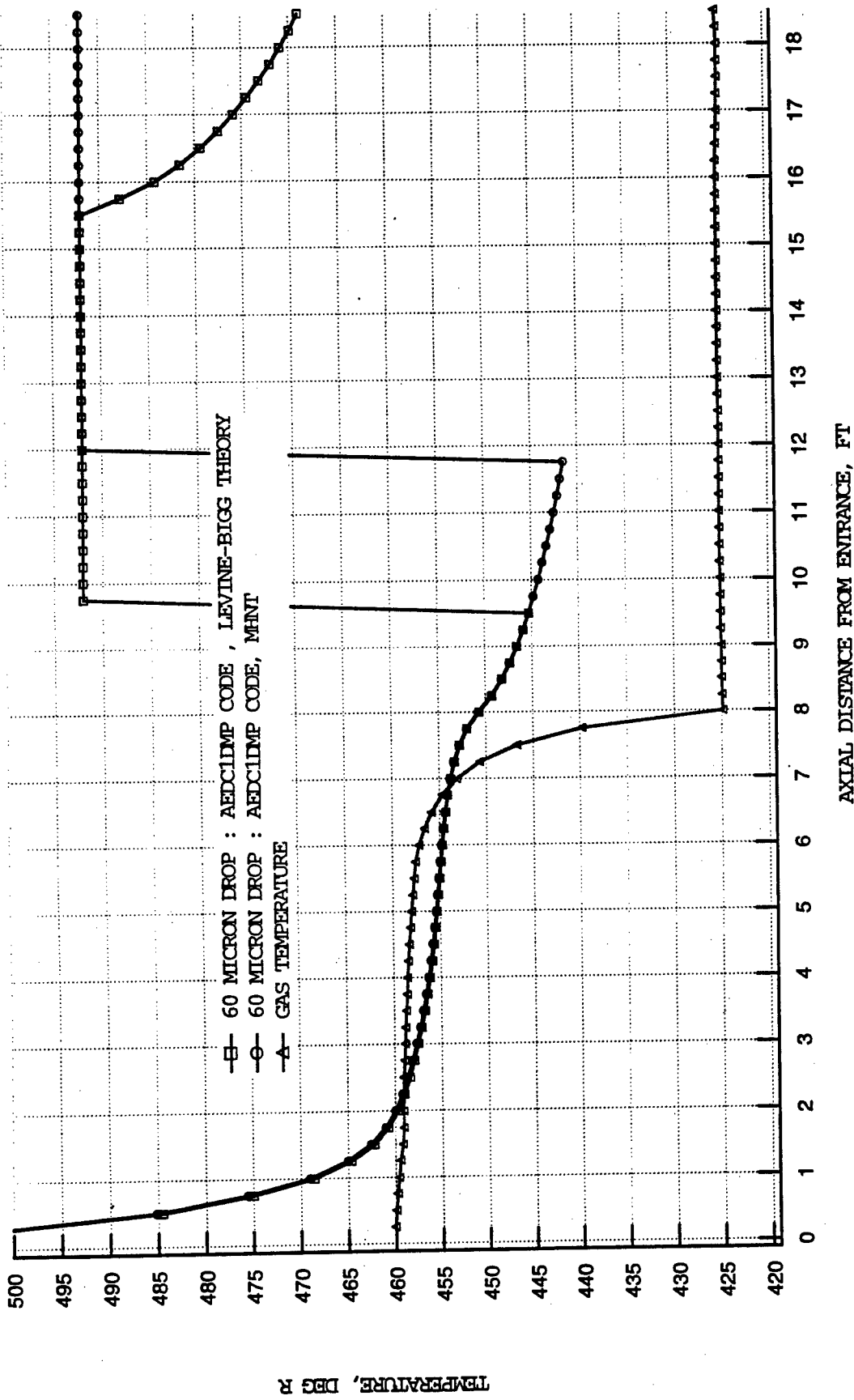


FIG. 12 (CONTINUED) COMPARISON OF PREDICTED PARTICLE TEMPERATURES DURING FREEZING: LEVINE-BIGG THEORY VS MODIFIED HOMOGENEOUS NUCLEATION THEORY (MINT)

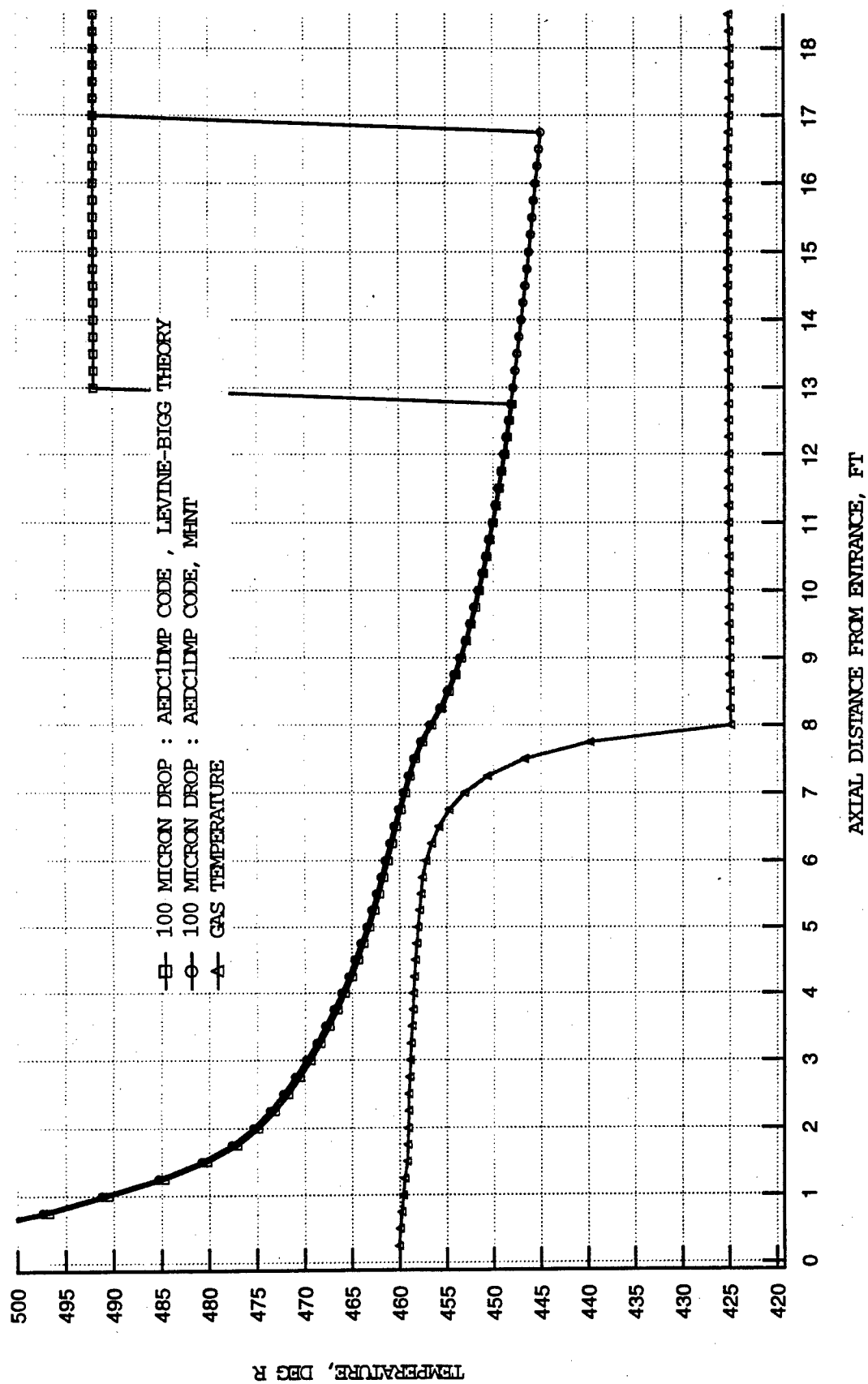


FIG. 12 (CONCLUDED) COMPARISON OF PREDICTED PARTICLE TEMPERATURES DURING FREEZING: LEVINE-BIGG THEORY VS MODIFIED HOMOGENEOUS NUCLEATION THEORY (MINT)

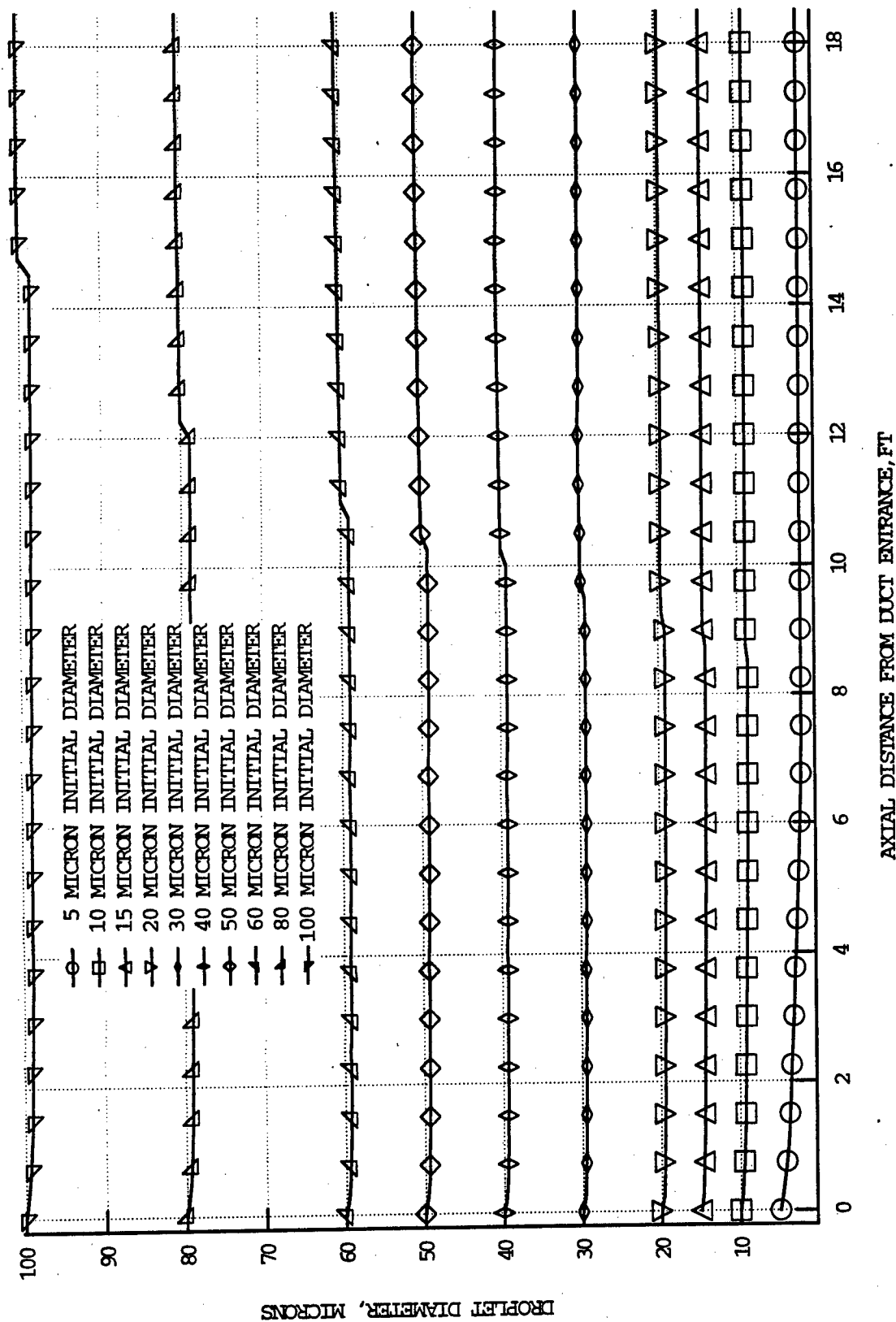


FIG. 13 PREDICTED VARIATIONS IN DROP SIZES ALONG THE DUCTED FLOW FREEZING PROCESS

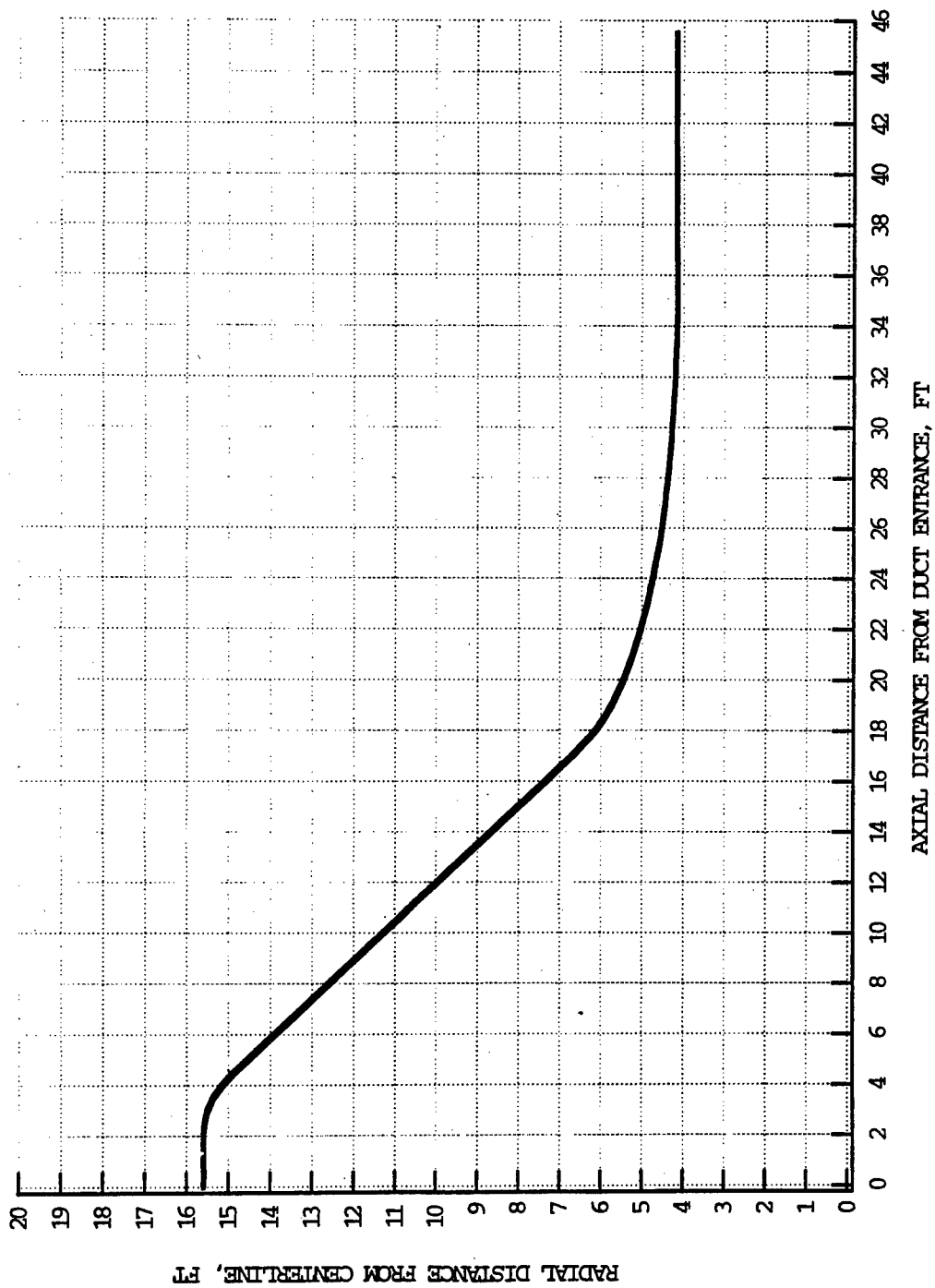


FIG. 14 DUCT WALL CONTOUR FOR REFERENCE CASE 2

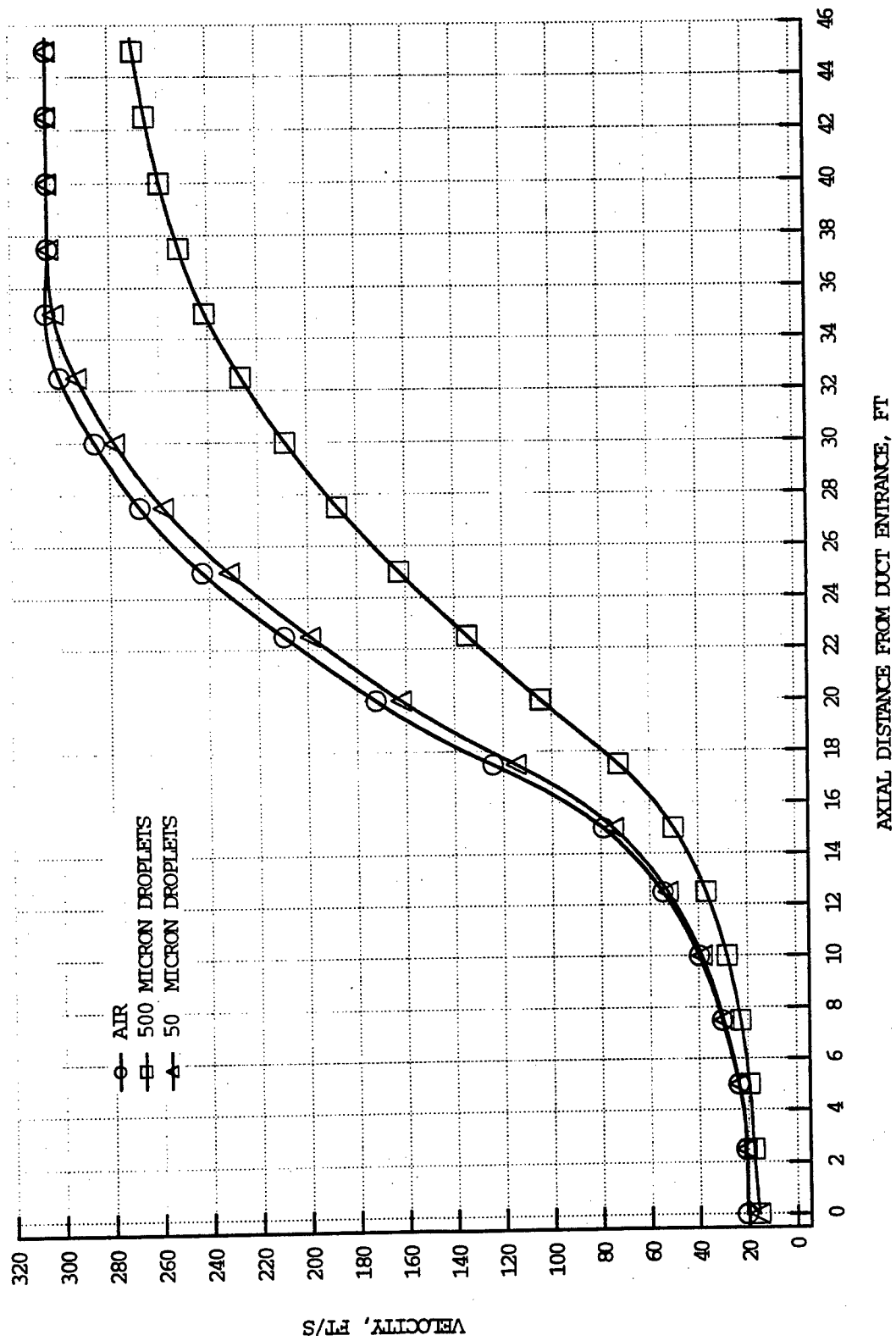


FIG. 15 PLOT OF AIR FLOW AND PARTICLE VELOCITIES FOR REFERENCE CASE 2

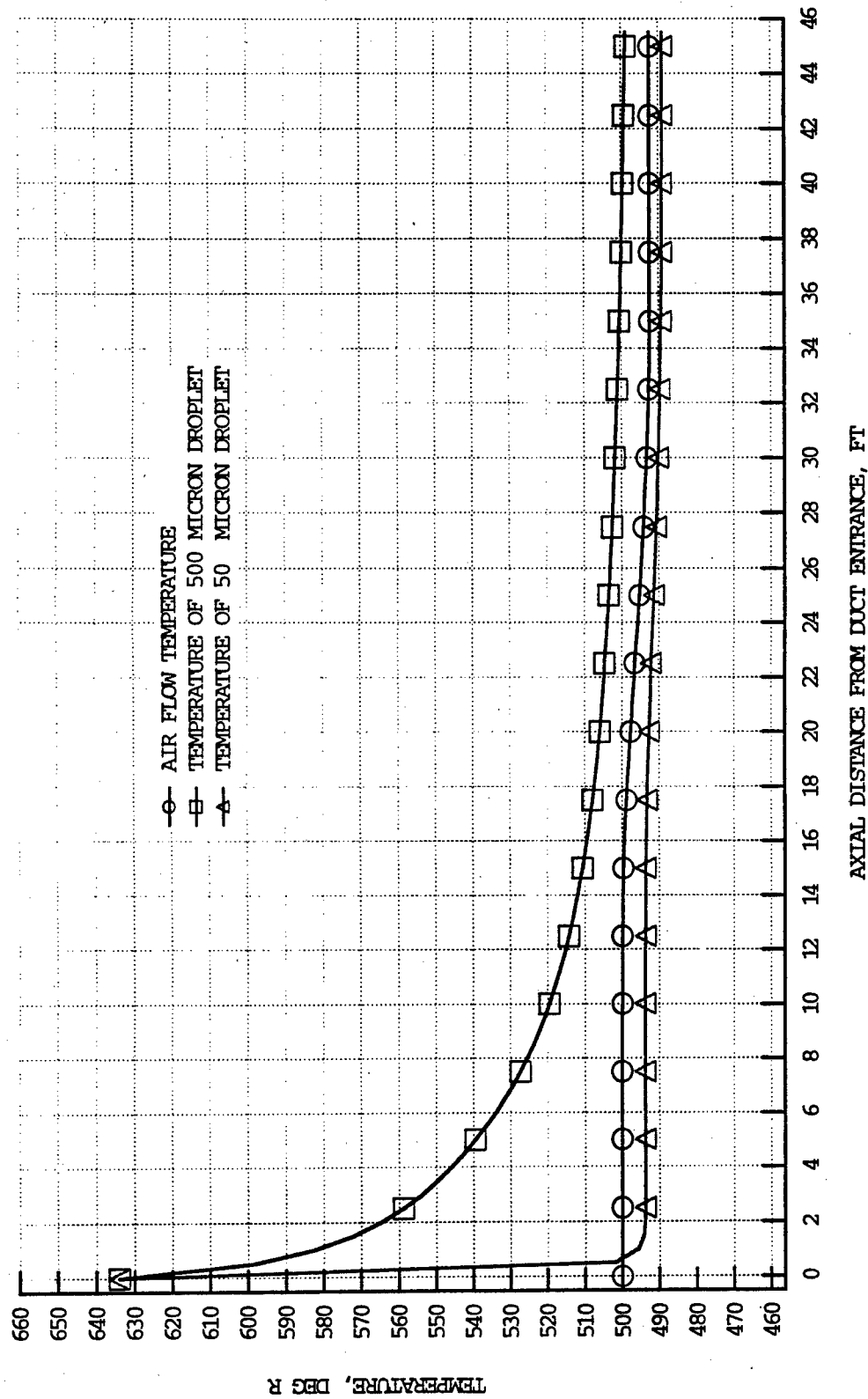


FIG. 16 PREDICTED AIR AND WATER PARTICLE TEMPERATURE VARIATIONS ALONG THE DUCTED FLOW, REFERENCE CASE 2

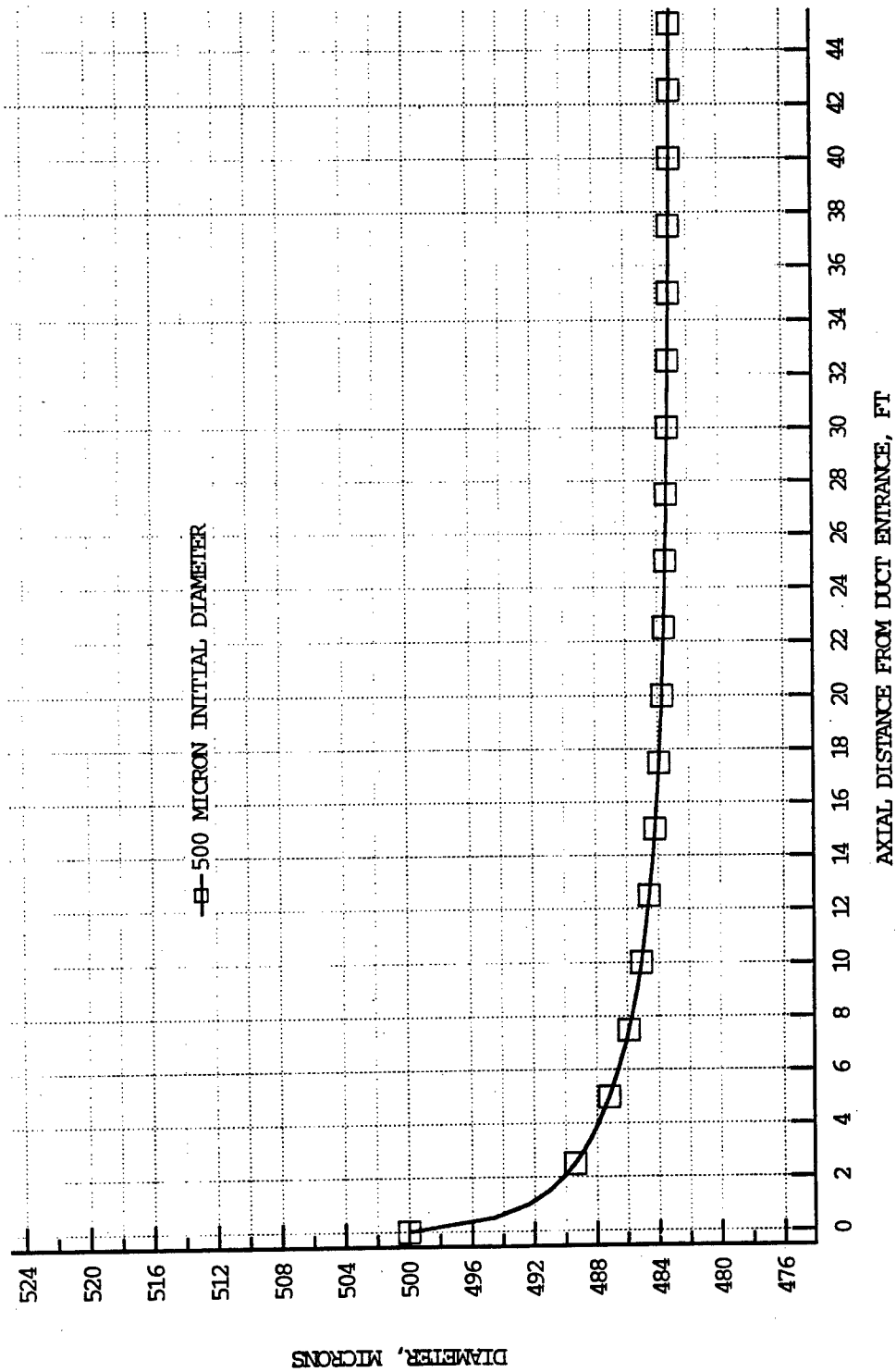


FIG. 17 PREDICTED VARIATIONS OF 50 AND 500 MICRON DROP SIZES ALONG THE DUCT FLOW, REFERENCE CASE 2

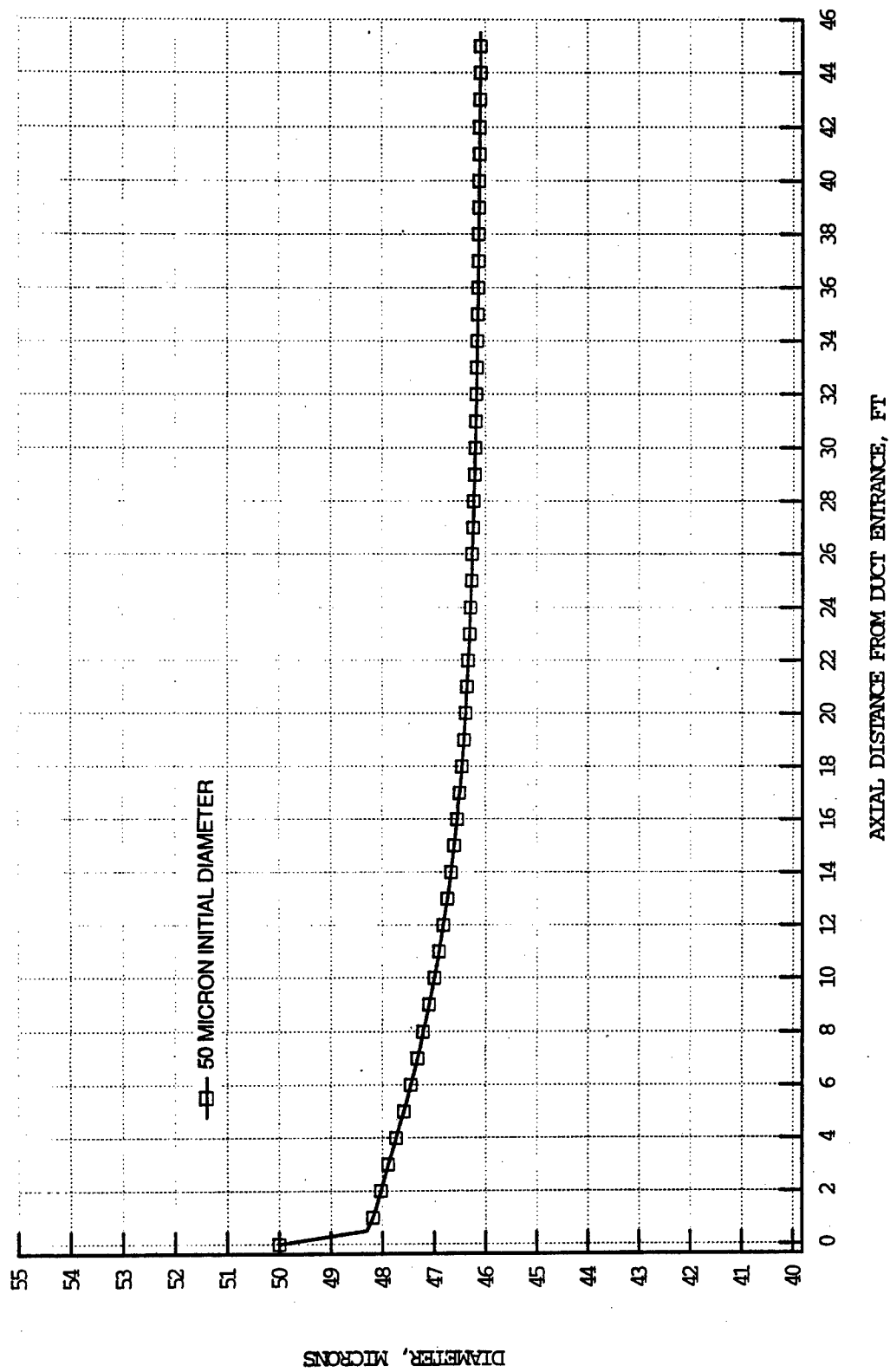


FIG. 17 (CONCLUDED) PREDICTED VARIATIONS OF 50 AND 500 MICRON DROP SIZES ALONG THE DUCT FLOW, REFERENCE CASE 2

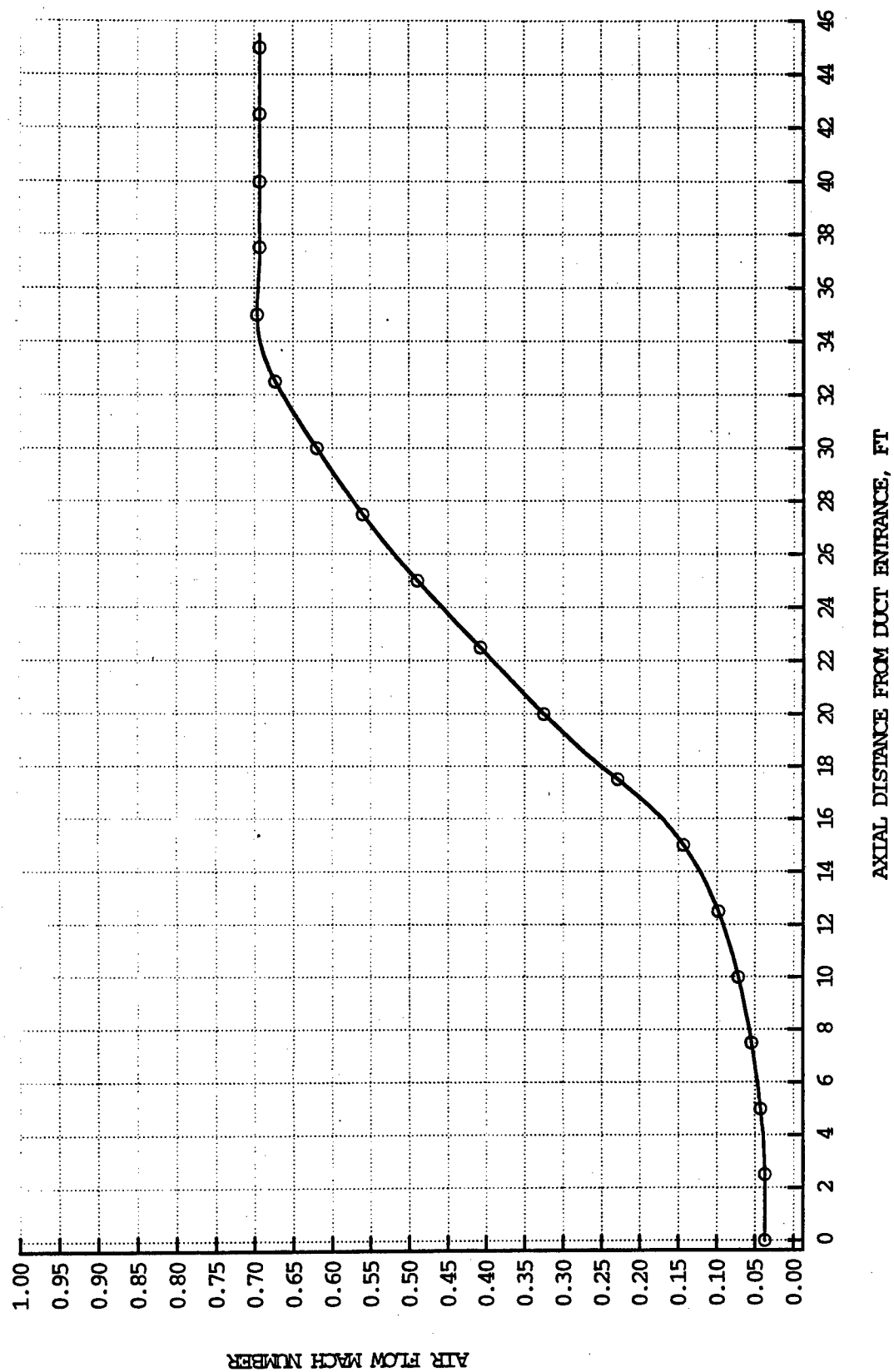


FIG. 18 PREDICTED AXIAL DISTRIBUTION OF AIR FLOW MACH NUMBER ALONG DUCTED FLOW

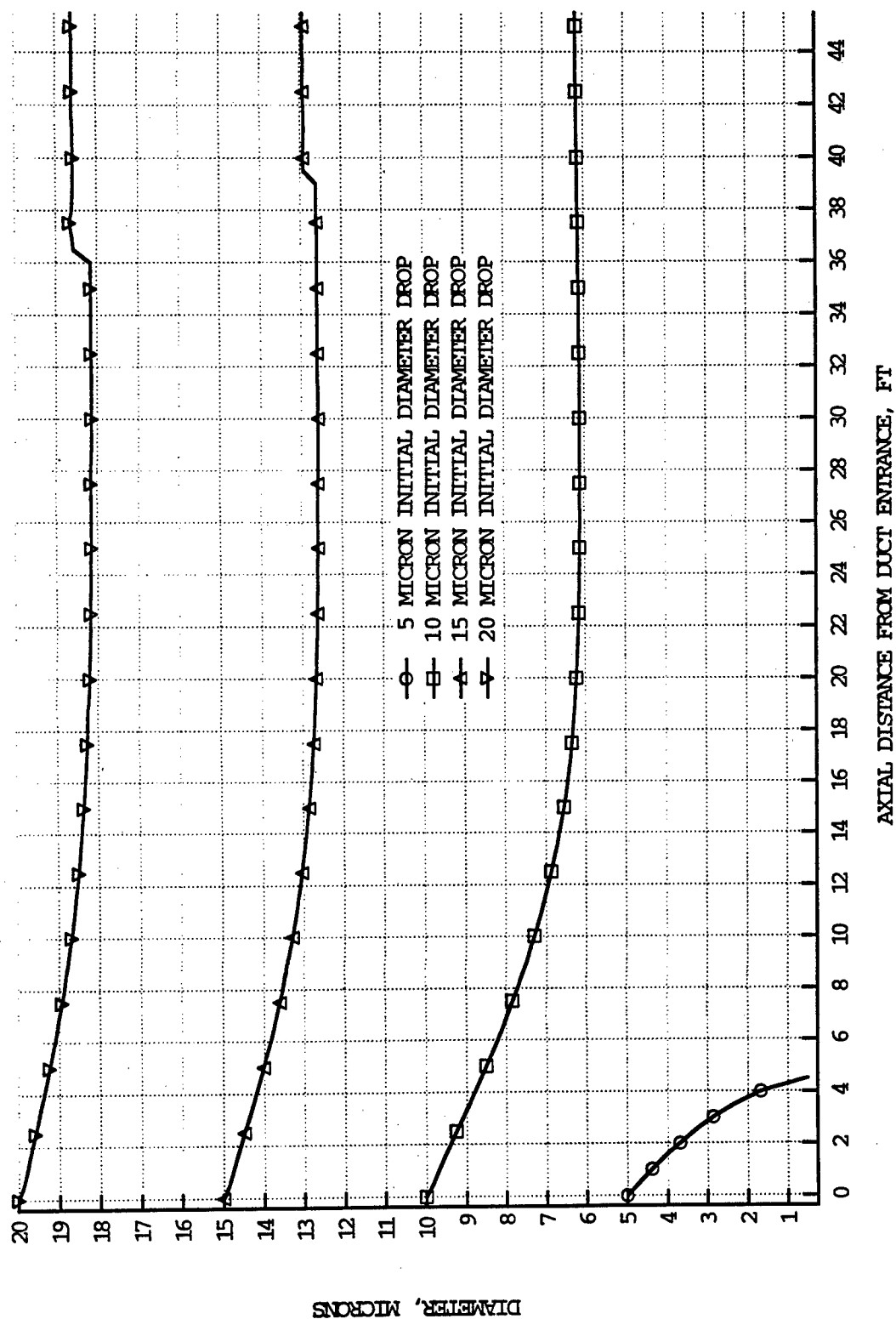


FIG. 19 PREDICTED AXIAL VARIATIONS OF WATER PARTICLE SIZES ALONG WIND TUNNEL FLOW

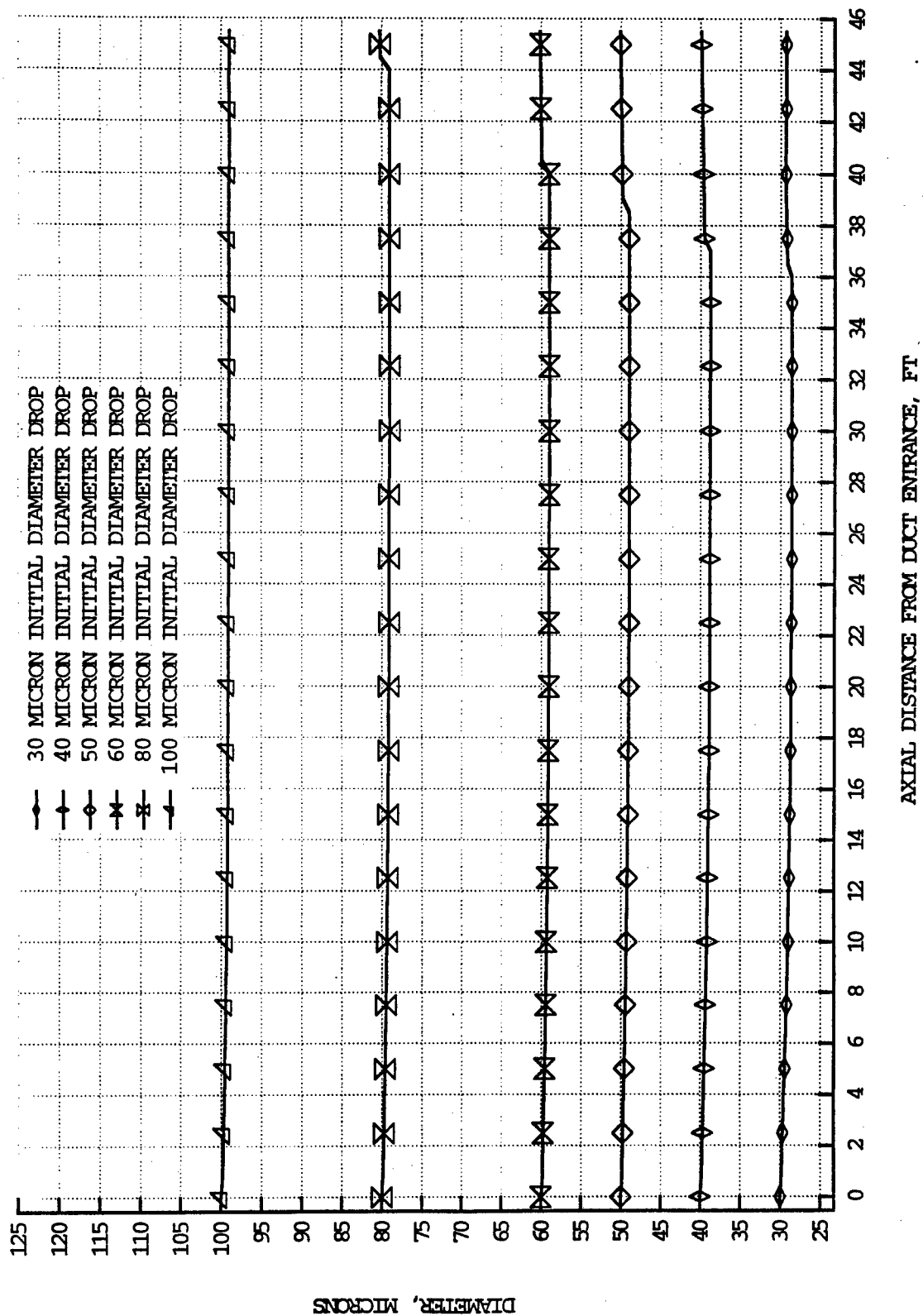


FIG. 19 (CONCLUDED) PREDICTED AXIAL VARIATIONS OF WATER PARTICLE SIZES ALONG WIND TUNNEL FLOW

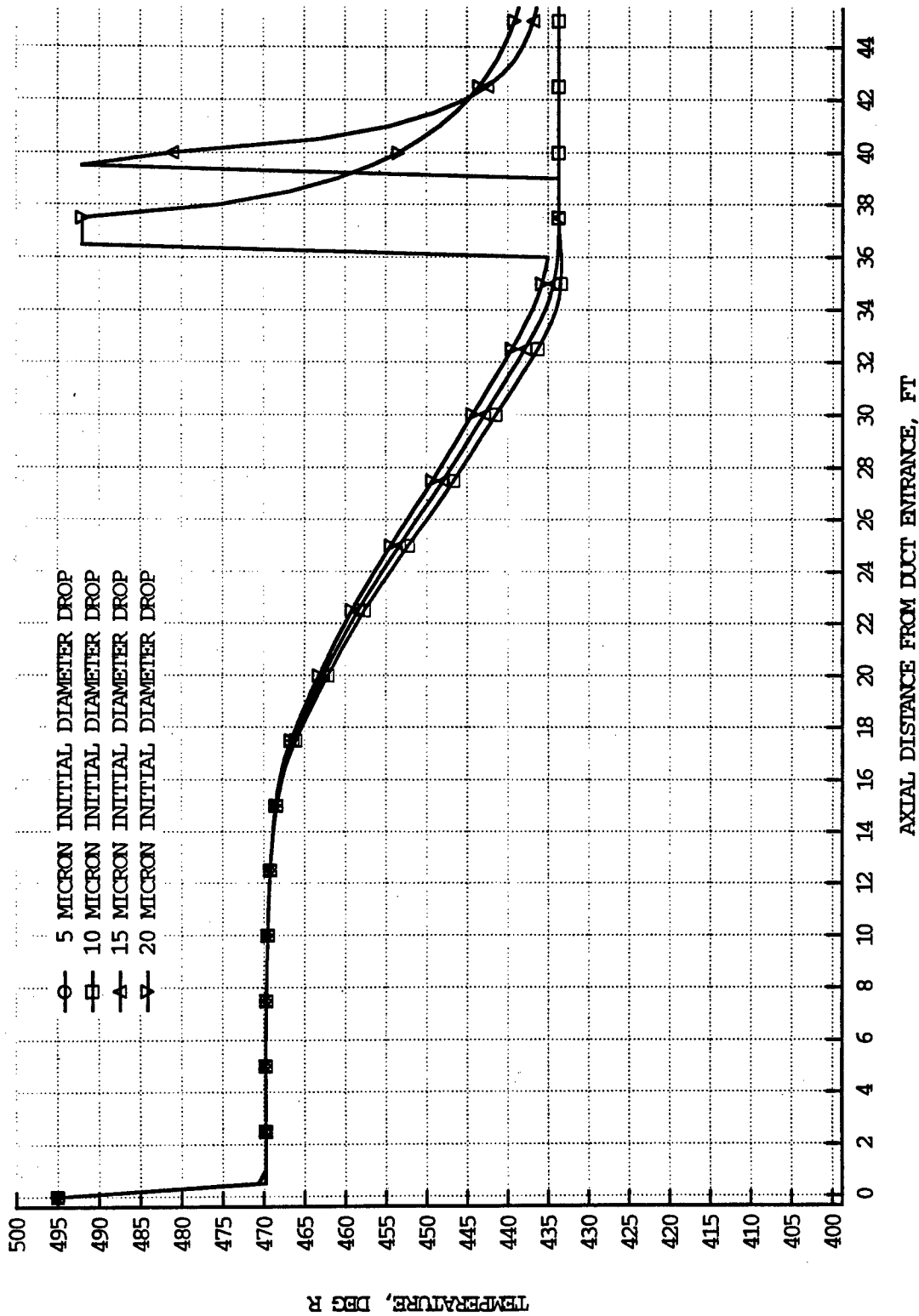


FIG. 20 PREDICTED AXIAL DISTRIBUTIONS OF WATER PARTICLE TEMPERATURES ALONG TUNNEL FLOW

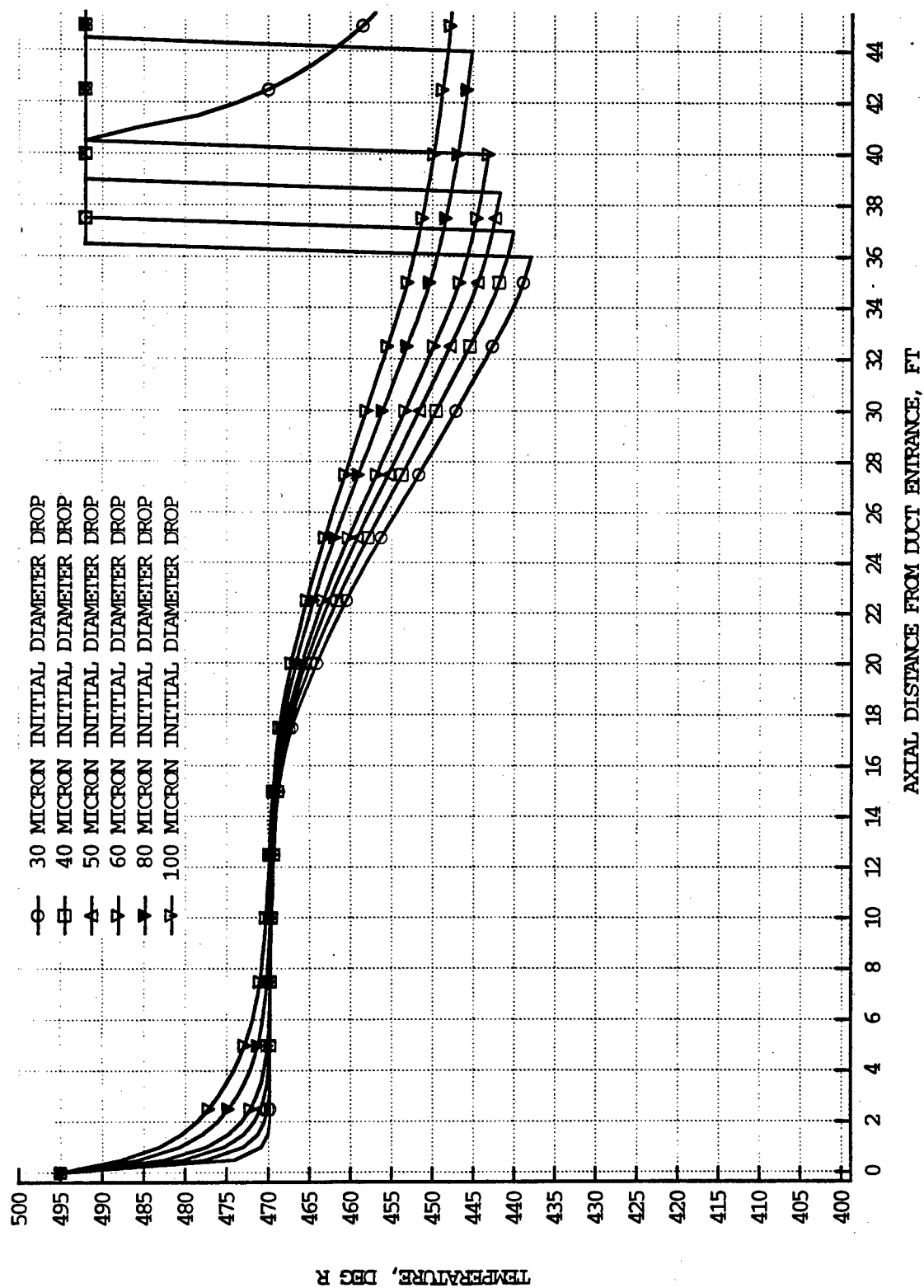


FIG. 20 (CONCLUDED) PREDICTED AXIAL DISTRIBUTIONS OF WATER PARTICLE TEMPERATURES ALONG TUNNEL FLOW

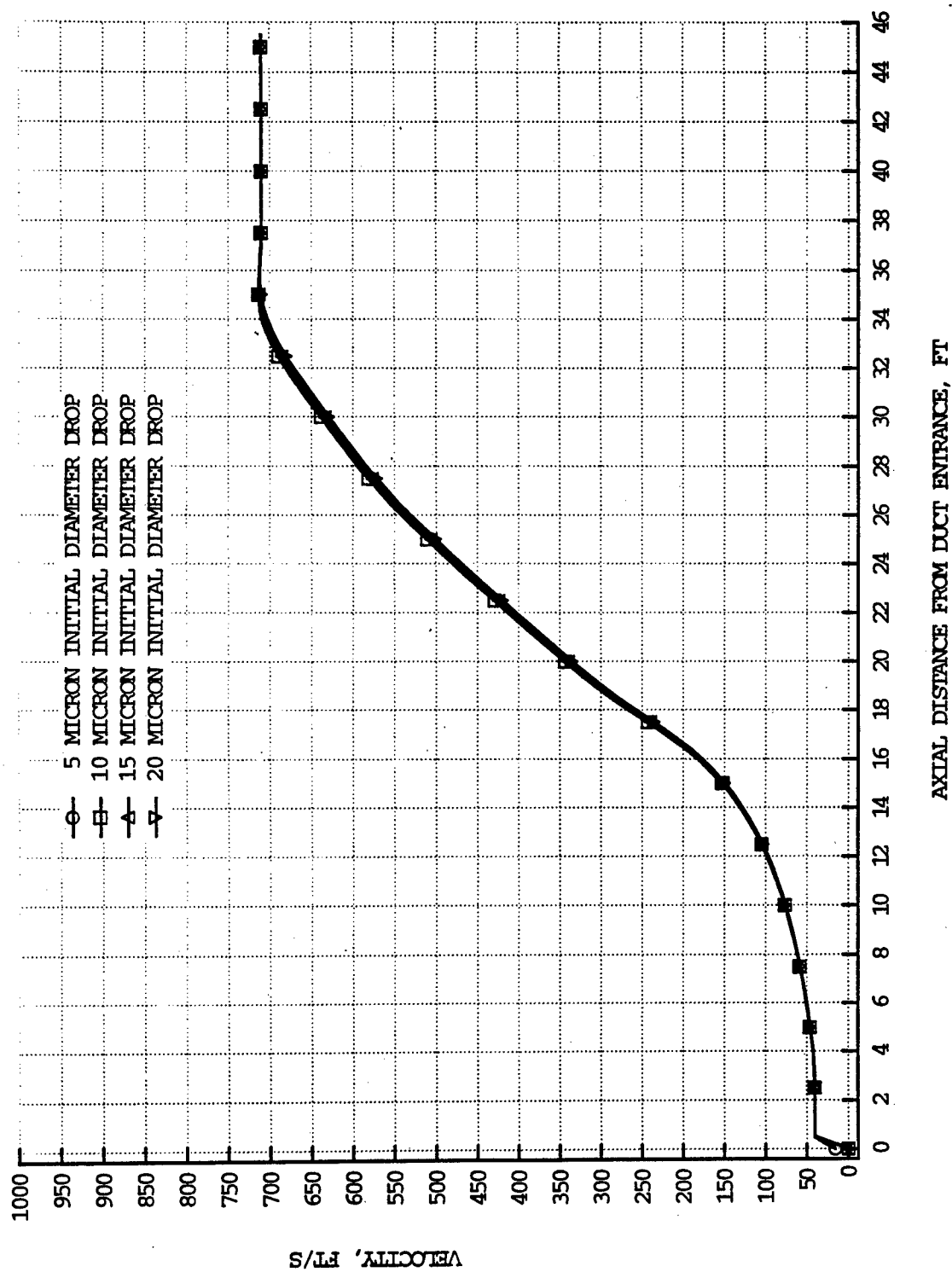


FIG. 21 PREDICTED VARIATIONS OF WATER PARTICLE VELOCITIES ALONG DUCT FLOW

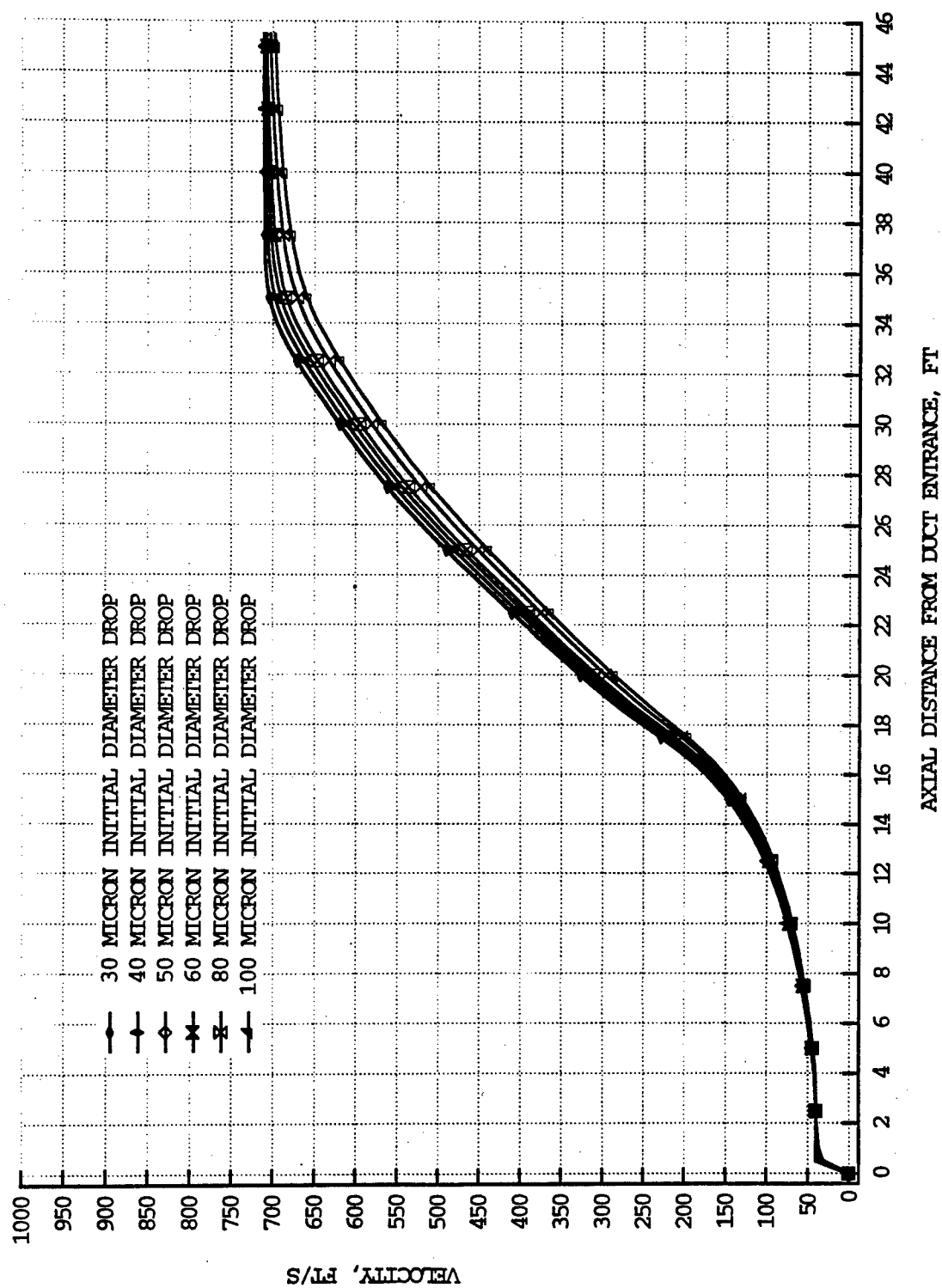


FIG. 21 (CONCLUDED) PREDICTED VARIATIONS OF WATER PARTICLE VELOCITIES ALONG DUCT FLOW

APPENDIX B

MASS AND ENERGY BALANCES FOR TWO-PHASE PARTICLE DURING FREEZING

B.1 The particle initially starts out as a two-phase mixture of water and ice in equilibrium. At the end of an integration step (or time, δt), the particle is still two-phase with a different ratio of ice mass to liquid mass because of freezing and evaporation that occurred during the period, δt . Heat transfer and mass transfer effects have changed the particle phase composition. Let the subscripts "I" refer to the solid or ice phase, and "L" refer to the liquid phase.

B.1.2 Particle Energy Change

The initial particle energy, E , at time t , is

$$E = M_I h_I + M_L h_L \quad (1)$$

The final particle energy at time $t + \delta t$ is

$$E' = M_I' h_I' + M_L' h_L' \quad (2)$$

The energy change is given by

$$\Delta E = E' - E = M_I' h_I' + M_L' h_L' - M_I h_I + M_L h_L \quad (3)$$

Because the process is isothermal,

$$h_I' = h_I \quad (4)$$

$$h_L' = h_L \quad (5)$$

Hence,

$$\Delta E = (M_I' - M_I) h_I + (M_L' - M_L) h_L \quad (6)$$

or

$$\Delta E = \Delta M_L h_L + \Delta M_L h_L \quad (7)$$

B.1.3 Liquid Mass Change by Evaporation

Evaporation of liquid mass occurs during the period, δt , in the amount

$$\delta M_L = \dot{M}_e'' A \delta t \quad (8)$$

where A is the surface area of the particle.

For a moving particle

$$\delta t = \frac{dx}{V} \quad (9)$$

where V is the particle velocity. Hence,

$$\delta M_L = \frac{\dot{M}_e'' A dx}{V} \quad (10)$$

The mass flux of evaporation is given by

$$\dot{M}_e'' = h_m \left(\frac{Y_s - Y_\infty}{1 - Y_s} \right) \quad (11)$$

where

$$h_m = \frac{h}{c_{p_f} L_e} \quad (12)$$

and

h = average convective heat transfer coefficient for the particle

L_e = the Lewis number for the particle "film" conditions

c_{p_f} = the specific heat of the "film" fluid

Y = mass fraction of vapor phase

Y_s = mass fraction at particle-gas "film" interface

Y_∞ = free stream mass fraction of vapor.

Thus,

$$\delta M_{L_e} = \frac{h A dx}{c_{p_f} L_e^m V} \left(\frac{Y_s - Y_\infty}{1 - Y_s} \right) \quad (13)$$

B.1.4 Total Liquid Mass Change

The total liquid mass change, ΔM_L , is thus in two parts: a part due to freezing of the liquid, with subscript L_f and a part due to evaporation, with subscript L_e . Hence,

$$-\Delta M_L = \delta M_{L_f} + \delta M_{L_e} \quad (14)$$

Clearly, however,

$$\delta M_{L_f} = \Delta M_I \quad (15)$$

Thus,

$$-\Delta M_L = \Delta M_I + \delta M_{L_e} \quad (16)$$

Solving,

$$\Delta M_L = -\Delta M_I - \delta M_{L_e} \quad (17)$$

B.1.5 Energy Balance Revisited

The energy balance can now be written

$$\Delta E = \Delta M_I h_I + \Delta M_L h_L \quad (18)$$

or, by substitution

$$\Delta E = \Delta M_I h_I + (-\Delta M_I - \delta M_{L_e}) h_L \quad (19)$$

$$\Delta E = \Delta M_I (h_I - h_L) - \delta M_{L_e} h_L \quad (20)$$

B.1.6 Heat Balance with Freestream

The energy balance for the particle must equal the energy lost or gained by the particle to the freestream. Thus,

$$\Delta E = -\dot{q}'' A \delta t - \dot{M}_e'' A h_v \delta t \quad (21)$$

where

$$\dot{q}'' = h(T_s - T_\infty) \quad (22)$$

and

h_v = the enthalpy of the vapor leaving the droplet.

Using previously defined parameters in equations (10), (11), (13) and (21), the energy flow from the particle is given by

$$\Delta E = -\frac{h A dx}{V} (T_s - T_\infty) - \frac{h A dx h_v}{c_{p,f} L_e'' V} \left(\frac{Y_s - Y_\infty}{1 - Y_s} \right) \quad (23)$$

B.1.7 Energy Equation Equality

The two energy equations for the particle can thus be combined by setting equation (20) equal to equation (21)

$$\Delta E = \Delta M_l (h_l - h_L) - \delta M_{L_e} h_L = -\dot{q}'' A \delta t - \dot{M}_e'' A h_v \delta t \quad (24)$$

Using equation (8) in equation (24)

$$\Delta E = \Delta M_l (h_l - h_L) - \delta M_{L_e} h_L = -\dot{q}'' A \delta t - \delta M_{L_e} h_v \quad (25)$$

Rearranging this equation

$$\Delta M_l (h_l - h_L) = -\dot{q}'' A \delta t - \delta M_{L_e} (h_v - h_L) \quad (26)$$

with

$$h_v - h_L = h_{fg} \quad (27)$$

where

h_{fg} = the enthalpy of evaporation of water

and

$$h_i - h_L = -H_F \quad (28)$$

where

H_F = the enthalpy of melting of ice

the energy balance becomes

$$\Delta M_i = \frac{\dot{q}'' A \delta t}{H_F} + \frac{\delta M_L h_{fg}}{H_F} \quad (29)$$

Using equations (9), (22) and (13) for δt , \dot{q}'' , and δM_L ,

$$\Delta M_i = \frac{h A dx}{V H_F} (T_s - T_\infty) + \frac{h A h_{fg} dx}{V c_{p,i} L_e^m H_F} \left(\frac{Y_s - Y_\infty}{1 - Y_s} \right) \quad (30)$$

Thus, the amount of ice produced is given by this expression. In words, the amount of ice produced equals the heat lost by convection and evaporation, divided by the heat of fusion of water.

B.2 Method for Adjusting Phase Masses During Freezing Process

Define the initial amount of mass of the particle as M_ϕ , where

$$M_\phi = \frac{\pi}{6} \rho_\phi D_\phi^3 = M_L + M_i \quad (31)$$

and the subscript “ ϕ ” refers to the initial values of the parameters before the integration step.

After computing ΔM_i and δM_L during the integration step, then determine the new values of the particle mass M_n as follows.

$$M_n = M_\phi - \delta M_L \quad (32)$$

But,

$$M_n = M_i' + M_L' \quad (33)$$

and

$$M_I' = M_I + \Delta M_I \quad (34)$$

thus,

$$M_L' = M_n - M_I' = M_L - \delta M_L - \Delta M_I \quad (35)$$

The mass fraction of the liquid phase is then given by

$$\alpha = M_L' / M_n \quad (36)$$

B.3 Particle Properties

The particle properties for the two-phase mixture particle of ice and liquid water are given in terms of α as follows:

average density

$$\bar{\rho} = \frac{\rho_L \rho_I}{\alpha \rho_I + (1 - \alpha) \rho_L} \quad (37)$$

average specific heat

$$\bar{c}_p = \alpha c_{pL} + (1 - \alpha) c_{pI} \quad (38)$$

average temperature

$$\bar{T} = T_L = T_I = 492^\circ R \text{ (isothermal assumption)} \quad (39)$$

APPENDIX C

FORTTRAN DATA INPUT FORMATS ("CARD IMAGES")

The following data input statements identify the data parameters that are input, their input order, and the ("card image") format that is required for their input. The term LCR is an acronym from the "old days" meaning line card reader. It is taken care of in the code compiling process, and is of no concern to users of the code.

```
READ(LCR,7) NXY,NUNITS,NCASES
READ(LCR,707)NFREZ
READ(LCR,8) (XS(I),YS(I),I=1,NXY)
READ(LCR,9) NSTA,XPRINT,DX0
READ(LCR,10) (ALP(I),I=1,10)
NS1=NSTA+1
READ(LCR,12) (STA(I),I=1,NS1)
READ(LCR,11) CV,VG,TG,P
READ(LCR,12) (FL(I),I=1,NSTA)
READ(LCR,12) (VL(I),I=1,NSTA)
READ(LCR,12) (TS(I),I=1,NSTA)
READ(LCR,12) (DMICRON(I),I=1,NSTA)
```

The actual input formats for the data are given below. They are extremely important because the code AEDC1DMP expects to read in the data in the defined format. Future releases of AEDC1DMP will use user friendly data input formats, but at present, this set of input formats must be used.

```
7  FORMAT(3I2)
707 FORMAT(1I2)
8  FORMAT(2E12.0)
9  FORMAT(1I2,2E12.0)
10 FORMAT(10A7)
11 FORMAT(4E10.0)
12 FORMAT(8E10.0)
```

APPENDIX D

SAMPLE DATA INPUT CASE

The data below are for a single data input case. Multiple cases can be run on AEDC1DMP by starting each new data set with card NSTA,XPRINT,DX0 and those that follow, through (DMICRON(I), I=1, NSTA) ; no spaces between data input sets.

800001

01

.0000	1.5788
.0250	1.42511
.0500	1.29351
.0750	1.18135
.1000	1.08625
.1250	1.00599
.1500	0.938571
.1750	0.882179
.2000	0.835174
.2250	0.796079
.2500	0.763576
.2750	0.736492
.3000	0.713789
.3250	0.694557
.3500	0.678003
.3750	0.663443
.4000	0.650297
.4250	0.638074
.4500	0.62637
.4750	0.614858
.5000	0.603283
.5250	0.59145
.5500	0.579224
.5750	0.566517
.6000	0.55329
.6250	0.539538
.6500	0.525291
.6750	0.510605
.7000	0.495562
.7250	0.48026
.7500	0.46481
.7750	0.449333
.8000	0.433958
.8250	0.418814
.8500	0.40403
.8750	0.38973

.9000	0.376034
.9250	0.36305
.9500	0.350879
.9750	0.339605
1.0000	0.3293
1.0250	0.320021
1.0500	0.311807
1.0750	0.304681
1.1000	0.298648
1.1250	0.293696
1.1500	0.289796
1.1750	0.2869
1.2000	0.284946
1.2250	0.283857
1.2500	0.283541
1.2750	0.283541
1.3000	0.283541
1.3250	0.283541
1.3500	0.283541
1.3750	0.283541
1.4000	0.283541
1.4250	0.283541
1.4500	0.283541
1.4750	0.283541
1.5000	0.283541
1.5250	0.283541
1.5500	0.283541
1.5750	0.283541
1.6000	0.283541
1.6250	0.283541
1.6500	0.283541
1.6750	0.283541
1.7000	0.283541
1.7250	0.283541
1.7500	0.283541
1.7750	0.283541
1.8000	0.283541
1.8250	0.283541
1.8500	0.283541
2.0000	0.283541
2.2000	0.283541
2.4000	0.283541
2.6000	0.283541
2.8000	0.283541
10	0.025

GENERIC NOZZLE GEOMETRY FOR PARAMETRIC FREEZING STUDY

0.0	0.02	0.04	0.06	0.08	0.10	0.12	0.14
0.16	0.18	2.70					
0.0002857	18.0	460.0	2116.0				
6.85E-05	2.06E-04	4.80E-04	3.62E-04	2.06E-04	3.43E-05	1.37E-05	1.37E-06
1.37E-07	1.37E-08						
46.	46.	46.	46.	46.	46.0	46.	46.
46.	46.						
543.	543.	543.	543.	543.	543.	543.	543.
543.	543.						
5.0	10.0	15.0	20.0	30.0	40.0	50.0	60.0
80.0	100.0						

APPENDIX E

DEFINITIONS OF THE DATA INPUT PARAMETERS

The definitions of the data input parameters for AEDC1DMP are the same, for the most part, as those in the original version of the code reported in Reference 53. Their specific definitions, and units, where necessary, are provided below.

NXY= THE NUMBER OF DUCT WALL COORDINATES INPUT

NUNITS=0 OR 1. IF NUNITS=0, ALL X AND Y COORDINATES, XPRINT, DX0, AND (STA(I), I=1, NS1) ARE INPUT IN UNITS OF FEET. IF NUNITS IS INPUT AS 1, THEN ALL SPACE COORDINATES ARE INPUT IN UNITS OF INCHES.

NCASES= THE NUMBER OF CASES INPUT TO BE COMPUTED.

NFREEZ= 0 OR 1. IF NFREEZ=0, THE WATER PARTICLE FREEZING MODEL IS NOT ACTIVATED; ALTERNATELY, FOR NFREEZ=1, THE MODEL WILL BE UTILIZED IN THE DUCT FLOW COMPUTATIONS.

**(XS(I), I=1, NXY)= THE AXIAL COORDINATES OF THE DUCT WALL CURVE.
(YS(I), I=1, NXY)=THE CORRESPONDING RADIAL COORDINATES OF THE DUCT WALL CURVE.**

NSTA= THE NUMBER OF WATER INJECTION STATIONS, WITH A MAXIMUM OF TEN(10).

**XPRINT= THE DISTANCE BETWEEN AXIAL LOCATIONS WHERE THE FLOW SOLUTION IS PRINTED OUT, AND, CONSEQUENTLY, STORED FOR INPUT TO DATA PLOTTING PROGRAMS SUCH AS WAVOMETRICS(R) IGOR™
PRO(<http://www.wavometrics.com/>).**

DX0= THE INITIAL NUMERICAL INTEGRATION STEP SIZE THAT THE USER DESIRES. BY SETTING DX0=0 OR BLANK, THE CODE SELECTS A DEFAULT STEP SIZE BASED ON THE DUCT LENGTH.

ALP= AN 80 COLUMN ALPHANUMERIC FILE IDENTIFIER.

(STA(I), I=1, NS1) = THE AXIAL LOCATIONS, OR STATIONS, WHERE WATER IS INJECTED INTO THE FLOW, PLUS, THE LAST VALUE, STA(NS1), WHICH INDICATES THE TERMINAL AXIAL LOCATION FOR FLOW SOLUTION. STA(NS1) USUALLY EQUALS XS(NXY) OR SLIGHTLY LESS.

CV= FLOW INITIAL SPECIFIC HUMIDITY, LBM OF WATER VAPOR/LBM OF DRY AIR.

VG= THE FLOW INITIAL VELOCITY, FT/SECOND.

TG= THE FLOW INITIAL STATIC TEMPERATURE, DEGREES RANKINE.

P= THE FLOW INITIAL STATIC PRESSURE, LBFORCE/SQUARE FOOT.

(FL(I), I=1, NSTA) = THE WATER LOADING INJECTED AT EACH STATION, LBM OF WATER/ LBM OF DRY AIR.

(VL(I), I=1,NSTA) = THE VELOCITIES OF THE WATER PARTICLES INJECTED AT THE WATER INJECTION STATIONS, FEET/SECOND.

(TS(I), I=1,NSTA) = THE TEMPERATURES OF THE WATER PARTICLES INJECTED AT EACH STATION, DEGREES RANKINE.

(DMICRONS(I), I=1,NSTA) = THE DIAMETERS OF THE WATER PARTICLES INJECTED AT EACH STATION, IN MICRONS (1 METER=1,000,000 MICRONS)

AS A POINT OF CLARIFICATION, FL(I), VL(I), TS(I), AND DMICRON(I) ALL CORRESPOND TO THE WATER PARTICLE CONDITIONS AT THE AXIAL INJECTION STATION LOCATED AT X=STA(I).

APPENDIX F

SAMPLE OUTPUT FROM CASE 3

A.E.D.C. ONE-DIMENSIONAL, MULTI-PHASE FLOW PROGRAM, AEDCLIMP
 DEVELOPED FROM THE CODE OF C.E.WILLBANKS AND R.J.SCHULZ (DESCRIBED IN AEDC TR 73-144)
 UNDER AEDC-UTSI TASK ORDER 97-03; TOM TIBBALS SVERDRUP TECHNOLOGY, INC., PROJECT MANAGER
 THIS VERSION DEVELOPED BY R.J. SCHULZ, UTSI, TULLAHOMA, TN 37388: DECEMBER, 1997
 THIS VERSION CONTAINS A DROPLET FREEZEOUT MODEL BASED ON MODIFIED HOMOGENEOUS NUCLEATION THEORY
 CALIBRATED TO THE DATA OF DORSCH AND HACKER, NACA TN 2142

INITIAL FLOW CONDITIONS AND THEIR UNITS:
 SPECIFIC HUMIDITY, CV, LEMS-WATER VAPOR/LBM-DRY AIR ; PRESSURE, P, PSFA ; TEMPERATURE, TG AND TS, DEG R
 VELOCITY, VG AND VL, FT/S ; WATER LOAD FACTOR, FL, LBM- LIQUID WATER/LBM-DRY AIR ;
 DROP DIA., D, MICRONS ; YDUCT=DUCT RADIUS, FT

IRT CASE 3 RADIAL: V=40 FT/SEC, T=15 DEG F, 10 DROP SIZES IN THE INLET

INLET SPECIFIC HUMIDITY= .000500000 INLET STATIC PRESSURE= 2073.60 INLET STATIC TEMPERATURE= 475.00
 AIR INLET VELOCITY= 40.000000 INLET RELATIVE HUMIDITY % = 25.997580 INITIAL FLtot= .000181611

INITIAL X= .000000 INITIAL INTEGRATION STEP SIZE, DX= .000700000

SPRAY CONDITIONS AT EACH INJECTION STATION ARE:

INJECTION STATION	1	2	3	4	5	6	7	8	9	10
XINJ(I)=	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
FL=	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
VL=	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000	.000000000
TS=	16.000000	16.000000	16.000000	16.000000	16.000000	16.000000	16.000000	16.000000	16.000000	16.000000
D=	5.000000	10.000000	15.000000	20.000000	30.000000	40.000000	50.000000	60.000000	80.000000	100.000000

INITIAL AREA= 763.166377

X=	.000000	YDUCT=	15.586000	MG=	.037269	PO=	2075.6258	TO=	475.133999
DX=	.000700000	A(X)=	763.1664	A(X)/AO=	1.00000	REL HUM. %	25.997580		
CV=	.000500000	VG=	40.000000	TG=	475.000000	P=	2073.60	FLtot=	.0000009060
FL=	.000009060	VL=	16.000000	TS=	495.000000	D=	5.00000	DMASS=	0.144222E-12
X=	.505403	YDUCT=	15.580455	MG=	.037296	PO=	2075.6254	TO=	475.125494
DX=	.007000000	A(X)=	762.6234	A(X)/AO=	.99929	REL HUM. %	26.311553		
CV=	.000505853	VG=	40.028167	TG=	474.991307	P=	2073.60	FLtot=	.000175752
FL=	.000007483	VL=	40.028233	TS=	469.748029	D=	4.69115	DMASS=	0.119113E-12
FL=	.000025949	VL=	40.028426	TS=	469.748086	D=	9.83222	DMASS=	0.109667E-11
FL=	.000061834	VL=	40.028634	TS=	469.853291	D=	14.86766	DMASS=	0.379184E-11
FL=	.000047021	VL=	40.027198	TS=	470.676583	D=	19.87691	DMASS=	0.906085E-11
FL=	.000026971	VL=	39.852714	TS=	474.090880	D=	29.87890	DMASS=	0.307763E-10
FL=	.000004499	VL=	39.094691	TS=	477.535286	D=	39.87783	DMASS=	0.731673E-10
FL=	.000001797	VL=	37.926089	TS=	480.267645	D=	49.87695	DMASS=	0.143160E-09
FL=	.000000180	VL=	36.500310	TS=	482.556906	D=	59.87860	DMASS=	0.247706E-09
FL=	.000000018	VL=	33.853338	TS=	485.638121	D=	79.88130	DMASS=	0.588109E-09
FL=	.000000002	VL=	31.467418	TS=	487.735676	D=	99.88631	DMASS=	0.114985E-08

X=	1.002403	YDUCT=	15.586023	MG=	.037268	PO=	2075.6254	TO=	475.106282
DX=	.007000000	A(X)=	763.1686	A(X)/AO=	1.00000	REL HUM. %=		26.559700	
CV=	.000510205	VG=	39.998143	TG=	474.972296	P=	2073.60	FLtot=	.000171396
FL=	.000006106	VL=	39.998347	TS=	469.750619	D=	4.38387	DMASS=	0.972066E-13
FL=	.000024832	VL=	39.999139	TS=	469.750927	D=	9.68905	DMASS=	0.104946E-11
FL=	.000060660	VL=	40.000448	TS=	469.751736	D=	14.77298	DMASS=	0.371986E-11
FL=	.000046510	VL=	40.002236	TS=	469.798763	D=	19.80466	DMASS=	0.896241E-11
FL=	.000026818	VL=	40.004206	TS=	470.859602	D=	29.82246	DMASS=	0.306022E-10
FL=	.000004480	VL=	39.935985	TS=	473.042335	D=	39.82218	DMASS=	0.728614E-10
FL=	.000001790	VL=	39.662687	TS=	475.331195	D=	49.81850	DMASS=	0.142657E-09
FL=	.000000179	VL=	39.157493	TS=	477.450015	D=	59.81580	DMASS=	0.246928E-09
FL=	.000000018	VL=	37.809281	TS=	480.746702	D=	79.81103	DMASS=	0.586558E-09
FL=	.000000002	VL=	36.306763	TS=	483.188061	D=	99.80941	DMASS=	0.114719E-08
X=	1.506403	YDUCT=	15.591582	MG=	.037241	PO=	2075.6255	TO=	475.087051
DX=	.007000000	A(X)=	763.7132	A(X)/AO=	1.00072	REL HUM. %=		26.802341	
CV=	.000514443	VG=	39.968286	TG=	474.953266	P=	2073.60	FLtot=	.000167154
FL=	.000004814	VL=	39.968332	TS=	469.752553	D=	4.04968	DMASS=	0.766273E-13
FL=	.000023719	VL=	39.968567	TS=	469.752738	D=	9.54214	DMASS=	0.100244E-11
FL=	.000059483	VL=	39.969053	TS=	469.753021	D=	14.67676	DMASS=	0.364765E-11
FL=	.000046005	VL=	39.969910	TS=	469.755634	D=	19.73266	DMASS=	0.886501E-11
FL=	.000026683	VL=	39.973143	TS=	470.039948	D=	29.77234	DMASS=	0.304482E-10
FL=	.000004465	VL=	39.971780	TS=	471.271519	D=	39.77991	DMASS=	0.726296E-10
FL=	.000001786	VL=	39.913617	TS=	473.002160	D=	49.77707	DMASS=	0.142302E-09
FL=	.000000179	VL=	39.729700	TS=	474.821225	D=	59.77310	DMASS=	0.246399E-09
FL=	.000000018	VL=	39.013419	TS=	477.971382	D=	79.76444	DMASS=	0.585532E-09
FL=	.000000002	VL=	38.027579	TS=	480.471680	D=	99.75864	DMASS=	0.114544E-08
X=	2.003403	YDUCT=	15.585958	MG=	.037268	PO=	2075.6256	TO=	475.068699
DX=	.007000000	A(X)=	763.1623	A(X)/AO=	.99999	REL HUM. %=		27.033525	
CV=	.000518466	VG=	39.995972	TG=	474.934728	P=	2073.60	FLtot=	.000163126
FL=	.000003648	VL=	39.995951	TS=	469.754228	D=	3.69212	DMASS=	0.580697E-13
FL=	.000022644	VL=	39.994442	TS=	469.754733	D=	9.39566	DMASS=	0.956984E-12
FL=	.000058335	VL=	39.992234	TS=	469.755127	D=	14.58171	DMASS=	0.357724E-11
FL=	.000045511	VL=	39.989520	TS=	469.755426	D=	19.66188	DMASS=	0.876996E-11
FL=	.000026555	VL=	39.983967	TS=	469.831073	D=	29.72471	DMASS=	0.303023E-10
FL=	.000004453	VL=	39.979770	TS=	470.471381	D=	39.74192	DMASS=	0.724218E-10
FL=	.000001782	VL=	39.964559	TS=	471.725164	D=	49.74249	DMASS=	0.142005E-09
FL=	.000000179	VL=	39.895277	TS=	473.242179	D=	59.73900	DMASS=	0.245978E-09
FL=	.000000018	VL=	39.501690	TS=	476.148065	D=	79.72861	DMASS=	0.584743E-09
FL=	.000000002	VL=	38.833277	TS=	478.604354	D=	99.72003	DMASS=	0.114412E-08
X=	2.501850	YDUCT=	15.563031	MG=	.037377	PO=	2075.6257	TO=	475.050919
DX=	.005638855	A(X)=	760.9187	A(X)/AO=	.99705	REL HUM. %=		27.258095	
CV=	.000522358	VG=	40.113036	TG=	474.916164	P=	2073.59	FLtot=	.000159231
FL=	.000002597	VL=	40.112750	TS=	469.755338	D=	3.29683	DMASS=	0.413439E-13
FL=	.000021584	VL=	40.108290	TS=	469.756334	D=	9.24676	DMASS=	0.912201E-12
FL=	.000057189	VL=	40.101820	TS=	469.757301	D=	14.48567	DMASS=	0.350702E-11

FL=	.000045016	VL=	40.093570	TS=	469.758098	D=	19.59031	DMASS=	0.867455E-11
FL=	.000026427	VL=	40.074340	TS=	469.778332	D=	29.67667	DMASS=	0.301556E-10
FL=	.000004440	VL=	40.055081	TS=	470.089864	D=	39.70441	DMASS=	0.722169E-10
FL=	.000001779	VL=	40.035744	TS=	470.949366	D=	49.70985	DMASS=	0.141726E-09
FL=	.000000178	VL=	39.998439	TS=	472.181726	D=	59.70830	DMASS=	0.245599E-09
FL=	.000000018	VL=	39.767285	TS=	474.816580	D=	79.69792	DMASS=	0.584068E-09
FL=	.000000002	VL=	39.301731	TS=	477.186334	D=	99.68758	DMASS=	0.114300E-08
X=	3.001806	YDUCT=	15.496723	MG=	.037698	PO=	2075.6257	TO=	475.033819
DX=	.004188597	A(X)=	754.4486	A(X)/A0=	.98858	REL HUM. %	27.475854		
CV=	.000526098	VG=	40.456645	TG=	474.896745	P=	2073.55	FLtot=	.000155486
FL=	.000001678	VL=	40.455718	TS=	469.755174	D=	2.84986	DMASS=	0.267050E-13
FL=	.000020543	VL=	40.445438	TS=	469.756869	D=	9.09569	DMASS=	0.868218E-12
FL=	.000056049	VL=	40.429719	TS=	469.758672	D=	14.38874	DMASS=	0.343709E-11
FL=	.000044519	VL=	40.409142	TS=	469.760386	D=	19.51795	DMASS=	0.857877E-11
FL=	.000026296	VL=	40.358204	TS=	469.767625	D=	29.62778	DMASS=	0.300068E-10
FL=	.000004427	VL=	40.302484	TS=	469.912620	D=	39.66646	DMASS=	0.720100E-10
FL=	.000001775	VL=	40.249274	TS=	470.469461	D=	49.67738	DMASS=	0.141449E-09
FL=	.000000178	VL=	40.195666	TS=	471.430484	D=	59.67853	DMASS=	0.245232E-09
FL=	.000000018	VL=	40.015843	TS=	473.777516	D=	79.66965	DMASS=	0.583447E-09
FL=	.000000002	VL=	39.667209	TS=	476.042268	D=	99.65853	DMASS=	0.114200E-08
X=	3.500972	YDUCT=	15.356598	MG=	.038390	PO=	2075.6258	TO=	475.017663
DX=	.002815455	A(X)=	740.8664	A(X)/A0=	.97078	REL HUM. %	27.684746		
CV=	.000529631	VG=	41.198292	TG=	474.875518	P=	2073.48	FLtot=	.000151949
FL=	.000000916	VL=	41.197230	TS=	469.752675	D=	2.32889	DMASS=	0.145737E-13
FL=	.000019534	VL=	41.178006	TS=	469.755233	D=	8.94416	DMASS=	0.825545E-12
FL=	.000054926	VL=	41.147575	TS=	469.758043	D=	14.29198	DMASS=	0.336821E-11
FL=	.000044025	VL=	41.107080	TS=	469.760899	D=	19.44551	DMASS=	0.848361E-11
FL=	.000026165	VL=	41.003412	TS=	469.766774	D=	29.57834	DMASS=	0.298568E-10
FL=	.000004414	VL=	40.884182	TS=	469.833668	D=	39.62792	DMASS=	0.718003E-10
FL=	.000001772	VL=	40.765148	TS=	470.178814	D=	49.64458	DMASS=	0.141169E-09
FL=	.000000178	VL=	40.653846	TS=	470.896491	D=	59.64872	DMASS=	0.244865E-09
FL=	.000000018	VL=	40.424227	TS=	472.930778	D=	79.64209	DMASS=	0.582842E-09
FL=	.000000002	VL=	40.107444	TS=	475.070452	D=	99.63098	DMASS=	0.114105E-08
X=	4.000846	YDUCT=	15.150661	MG=	.039442	PO=	2075.6258	TO=	475.002683
DX=	.001529440	A(X)=	721.1291	A(X)/A0=	.94492	REL HUM. %	27.881960		
CV=	.000532907	VG=	42.326375	TG=	474.852647	P=	2073.36	FLtot=	.000148669
FL=	.000000338	VL=	42.325566	TS=	469.747752	D=	1.67110	DMASS=	0.538430E-14
FL=	.000018562	VL=	42.297155	TS=	469.751070	D=	8.79328	DMASS=	0.784468E-12
FL=	.000053829	VL=	42.252030	TS=	469.754700	D=	14.19622	DMASS=	0.330096E-11
FL=	.000043540	VL=	42.191885	TS=	469.758514	D=	19.37371	DMASS=	0.838998E-11
FL=	.000026034	VL=	42.036678	TS=	469.765837	D=	29.52892	DMASS=	0.297074E-10
FL=	.000004402	VL=	41.852691	TS=	469.798869	D=	39.58911	DMASS=	0.715896E-10
FL=	.000001768	VL=	41.659692	TS=	470.007443	D=	49.61153	DMASS=	0.140887E-09
FL=	.000000178	VL=	41.472283	TS=	470.525547	D=	59.61879	DMASS=	0.244496E-09
FL=	.000000018	VL=	41.124067	TS=	472.238286	D=	79.61466	DMASS=	0.582240E-09
FL=	.000000002	VL=	40.761853	TS=	474.223169	D=	99.60392	DMASS=	0.114012E-08

X=	4.500032	YDUCT=	14.863179	MG=	.040985	PO=	2075.6259	TO=	474.989305
DX=	.000145041	A(X)=	694.0221	A(X)/AO=	.90940	REL HUM. %=		28.063372	
CV=	.000535833	VG=	43.980740	TG=	474.827312	P=	2073.18	FLtot=	.000145741
FL=	.000000010	VL=	43.980952	TS=	469.739348	D=	.51070	DMASS=	0.153680E-15
FL=	.000017638	VL=	43.940378	TS=	469.743671	D=	8.64490	DMASS=	0.745423E-12
FL=	.000052771	VL=	43.875367	TS=	469.748320	D=	14.10257	DMASS=	0.323607E-11
FL=	.000043067	VL=	43.788430	TS=	469.753263	D=	19.30336	DMASS=	0.829891E-11
FL=	.000025905	VL=	43.563088	TS=	469.762727	D=	29.48009	DMASS=	0.295603E-10
FL=	.000004389	VL=	43.295489	TS=	469.782241	D=	39.55046	DMASS=	0.713801E-10
FL=	.000001765	VL=	43.013052	TS=	469.907805	D=	49.57853	DMASS=	0.140606E-09
FL=	.000000177	VL=	42.734591	TS=	470.273892	D=	59.58897	DMASS=	0.244129E-09
FL=	.000000018	VL=	42.221708	TS=	471.682776	D=	79.58745	DMASS=	0.581643E-09
FL=	.000000002	VL=	41.750345	TS=	473.488318	D=	99.57717	DMASS=	0.113920E-08
X=	5.000321	YDUCT=	14.537372	MG=	.042850	PO=	2075.6259	TO=	474.977925
DX=	.007000000	A(X)=	663.9291	A(X)/AO=	.86997	REL HUM. %=		28.222983	
CV=	.000538322	VG=	45.980515	TG=	474.800865	P=	2072.95	FLtot=	.000143248
FL=	.000016765	VL=	45.933460	TS=	469.733311	D=	8.49997	DMASS=	0.708557E-12
FL=	.000051758	VL=	45.854962	TS=	469.738670	D=	14.01176	DMASS=	0.317395E-11
FL=	.000042612	VL=	45.749683	TS=	469.744487	D=	19.23508	DMASS=	0.821116E-11
FL=	.000025780	VL=	45.474849	TS=	469.756118	D=	29.43240	DMASS=	0.294171E-10
FL=	.000004376	VL=	45.142701	TS=	469.771240	D=	39.51243	DMASS=	0.711744E-10
FL=	.000001761	VL=	44.784044	TS=	469.848686	D=	49.54594	DMASS=	0.140329E-09
FL=	.000000177	VL=	44.422190	TS=	470.105047	D=	59.55952	DMASS=	0.243768E-09
FL=	.000000018	VL=	43.740293	TS=	471.245687	D=	79.56065	DMASS=	0.581055E-09
FL=	.000000002	VL=	43.128640	TS=	472.860300	D=	99.55085	DMASS=	0.113830E-08
X=	5.504321	YDUCT=	14.210681	MG=	.044847	PO=	2075.6259	TO=	474.967115
DX=	.007000000	A(X)=	634.4241	A(X)/AO=	.83131	REL HUM. %=		28.377526	
CV=	.000540687	VG=	48.122271	TG=	474.773176	P=	2072.69	FLtot=	.000140881
FL=	.000015941	VL=	48.072574	TS=	469.721217	D=	8.35837	DMASS=	0.673733E-12
FL=	.000050790	VL=	47.986845	TS=	469.726982	D=	13.92382	DMASS=	0.311456E-11
FL=	.000042174	VL=	47.871860	TS=	469.733323	D=	19.16903	DMASS=	0.812686E-11
FL=	.000025658	VL=	47.570706	TS=	469.746536	D=	29.38615	DMASS=	0.292786E-10
FL=	.000004364	VL=	47.202023	TS=	469.760852	D=	39.47537	DMASS=	0.709743E-10
FL=	.000001758	VL=	46.795862	TS=	469.811318	D=	49.51408	DMASS=	0.140058E-09
FL=	.000000177	VL=	46.376891	TS=	469.991531	D=	59.53075	DMASS=	0.243415E-09
FL=	.000000018	VL=	45.563690	TS=	470.907855	D=	79.53458	DMASS=	0.580484E-09
FL=	.000000002	VL=	44.822954	TS=	472.334399	D=	99.52528	DMASS=	0.113742E-08
X=	6.001321	YDUCT=	13.883709	MG=	.046989	PO=	2075.6259	TO=	474.957027
DX=	.007000000	A(X)=	605.5651	A(X)/AO=	.79349	REL HUM. %=		28.525340	
CV=	.000542894	VG=	50.419719	TG=	474.744128	P=	2072.41	FLtot=	.000138672
FL=	.000015180	VL=	50.365361	TS=	469.707547	D=	8.22308	DMASS=	0.641544E-12
FL=	.000049883	VL=	50.268484	TS=	469.713869	D=	13.84049	DMASS=	0.305898E-11
FL=	.000041763	VL=	50.138800	TS=	469.720799	D=	19.10651	DMASS=	0.804760E-11
FL=	.000025544	VL=	49.800776	TS=	469.735280	D=	29.34229	DMASS=	0.291477E-10
FL=	.000004352	VL=	49.390626	TS=	469.749966	D=	39.44015	DMASS=	0.707845E-10
FL=	.000001755	VL=	48.940955	TS=	469.785733	D=	49.48376	DMASS=	0.139801E-09

FL=	.000000177	VL=	48.475664	TS=	469.914980	D=	59.50338	DMASS=	0.243079E-09
FL=	.000000018	VL=	47.560113	TS=	470.653239	D=	79.50992	DMASS=	0.579945E-09
FL=	.000000002	VL=	46.712606	TS=	471.908075	D=	99.50119	DMASS=	0.113660E-08
X=	6.505321	YDUCT=	13.554534	MG=	.049306	PO=	2075.6260	TO=	474.947359
DX=	.007000000	A(X)=	577.1904	A(X)/AO=	.75631	REL HUM. %=	28.670749		
CV=	.000545009	VG=	52.903465	TG=	474.712968	P=	2072.08	FLtot=	.000136554
FL=	.000014457	VL=	52.844621	TS=	469.691833	D=	8.09038	DMASS=	0.610983E-12
FL=	.000049012	VL=	52.736694	TS=	469.698715	D=	13.75946	DMASS=	0.300557E-11
FL=	.000041366	VL=	52.592599	TS=	469.706258	D=	19.04574	DMASS=	0.797106E-11
FL=	.000025432	VL=	52.218604	TS=	469.722060	D=	29.29958	DMASS=	0.290206E-10
FL=	.000004341	VL=	51.766881	TS=	469.737665	D=	39.40575	DMASS=	0.705995E-10
FL=	.000001751	VL=	51.273484	TS=	469.765347	D=	49.45409	DMASS=	0.139550E-09
FL=	.000000176	VL=	50.763666	TS=	469.859682	D=	59.47662	DMASS=	0.242751E-09
FL=	.000000018	VL=	49.756195	TS=	470.454574	D=	79.48594	DMASS=	0.579420E-09
FL=	.000000002	VL=	48.814411	TS=	471.553064	D=	99.47788	DMASS=	0.113580E-08
X=	7.002321	YDUCT=	13.230057	MG=	.051761	PO=	2075.6260	TO=	474.938351
DX=	.007000000	A(X)=	549.8868	A(X)/AO=	.72053	REL HUM. %=	28.810572		
CV=	.000546980	VG=	55.536401	TG=	474.680049	P=	2071.72	FLtot=	.000134581
FL=	.000013789	VL=	55.472082	TS=	469.674223	D=	7.96394	DMASS=	0.582781E-12
FL=	.000048198	VL=	55.350648	TS=	469.681770	D=	13.68287	DMASS=	0.295566E-11
FL=	.000040993	VL=	55.189073	TS=	469.690014	D=	18.98836	DMASS=	0.789923E-11
FL=	.000025327	VL=	54.772454	TS=	469.707217	D=	29.25916	DMASS=	0.289007E-10
FL=	.000004330	VL=	54.273834	TS=	469.723995	D=	39.37311	DMASS=	0.704242E-10
FL=	.000001748	VL=	53.733357	TS=	469.747558	D=	49.42587	DMASS=	0.139311E-09
FL=	.000000176	VL=	53.177653	TS=	469.818719	D=	59.45117	DMASS=	0.242440E-09
FL=	.000000018	VL=	52.081514	TS=	470.302148	D=	79.46324	DMASS=	0.578924E-09
FL=	.000000002	VL=	51.053341	TS=	471.264691	D=	99.45594	DMASS=	0.113505E-08
X=	7.506321	YDUCT=	12.901450	MG=	.054441	PO=	2075.6260	TO=	474.929727
DX=	.007000000	A(X)=	522.9099	A(X)/AO=	.68518	REL HUM. %=	28.949491		
CV=	.000548867	VG=	58.409065	TG=	474.644011	P=	2071.31	FLtot=	.000132692
FL=	.000013157	VL=	58.338447	TS=	469.653880	D=	7.84021	DMASS=	0.556040E-12
FL=	.000047417	VL=	58.201307	TS=	469.662199	D=	13.60853	DMASS=	0.290774E-11
FL=	.000040633	VL=	58.019540	TS=	469.671261	D=	18.93267	DMASS=	0.782993E-11
FL=	.000025225	VL=	57.554110	TS=	469.690087	D=	29.21984	DMASS=	0.287843E-10
FL=	.000004319	VL=	57.002091	TS=	469.708286	D=	39.34126	DMASS=	0.702534E-10
FL=	.000001745	VL=	56.408501	TS=	469.729982	D=	49.39828	DMASS=	0.139078E-09
FL=	.000000176	VL=	55.801943	TS=	469.785399	D=	59.42626	DMASS=	0.242135E-09
FL=	.000000018	VL=	54.611424	TS=	470.179977	D=	79.44110	DMASS=	0.578440E-09
FL=	.000000002	VL=	53.495855	TS=	471.022242	D=	99.43464	DMASS=	0.113432E-08
X=	8.003321	YDUCT=	12.577403	MG=	.057293	PO=	2075.6260	TO=	474.921703
DX=	.007000000	A(X)=	496.9719	A(X)/AO=	.65120	REL HUM. %=	29.084525		
CV=	.000550624	VG=	61.466625	TG=	474.605291	P=	2070.84	FLtot=	.000130934
FL=	.000012574	VL=	61.388770	TS=	469.630963	D=	7.72267	DMASS=	0.531404E-12
FL=	.000046688	VL=	61.233472	TS=	469.640173	D=	13.53844	DMASS=	0.286304E-11
FL=	.000040296	VL=	61.028521	TS=	469.650173	D=	18.88016	DMASS=	0.776497E-11

FL= .000025129 VL= 60.507740 TS= 469.670840 D= 29.18265 DMAS= 0.286746E-10
FL= .000004309 VL= 59.896116 TS= 469.690675 D= 39.31105 DMAS= 0.700917E-10
FL= .000001743 VL= 59.243963 TS= 469.711943 D= 49.37205 DMAS= 0.138856E-09
FL= .000000176 VL= 58.581957 TS= 469.757095 D= 59.40254 DMAS= 0.241845E-09
FL= .000000018 VL= 57.290776 TS= 470.082954 D= 79.42007 DMAS= 0.577981E-09
FL= .000000002 VL= 56.085222 TS= 470.822451 D= 99.41451 DMAS= 0.113363E-08

X= 8.500321 YDUCT= 12.252924 MG= .060380 PO= 2075.6260 TO= 474.914136
DX= .007000000 A(X)= 471.6604 A(X)/A0= .61803 REL HUM. %= 29.218605

CV= .000552280 VG= 64.776279 TG= 474.562732 P= 2070.31 FLtot= .000129276
FL= .000012029 VL= 64.690031 TS= 469.604705 D= 7.60957 DMAS= 0.508398E-12
FL= .000045999 VL= 64.513432 TS= 469.614963 D= 13.47148 DMAS= 0.282077E-11
FL= .000039976 VL= 64.281456 TS= 469.626065 D= 18.83000 DMAS= 0.770324E-11
FL= .000025037 VL= 63.696868 TS= 469.648875 D= 29.14702 DMAS= 0.285696E-10
FL= .000004300 VL= 63.017484 TS= 469.670610 D= 39.28200 DMAS= 0.699364E-10
FL= .000001740 VL= 62.299511 TS= 469.692388 D= 49.34675 DMAS= 0.138643E-09
FL= .000000175 VL= 61.575751 TS= 469.730914 D= 59.37964 DMAS= 0.241566E-09
FL= .000000018 VL= 60.173987 TS= 470.002904 D= 79.39977 DMAS= 0.577538E-09
FL= .000000002 VL= 58.871783 TS= 470.653685 D= 99.39516 DMAS= 0.113297E-08

X= 9.004321 YDUCT= 11.923750 MG= .063776 PO= 2075.6260 TO= 474.906909
DX= .007000000 A(X)= 446.6585 A(X)/A0= .58527 REL HUM. %= 29.354661

CV= .000553863 VG= 68.415869 TG= 474.514906 P= 2069.70 FLtot= .000127691
FL= .000011515 VL= 68.319864 TS= 469.574101 D= 7.49946 DMAS= 0.486646E-12
FL= .000045339 VL= 68.118231 TS= 469.585604 D= 13.40673 DMAS= 0.278030E-11
FL= .000039667 VL= 67.854735 TS= 469.598013 D= 18.78146 DMAS= 0.764380E-11
FL= .000024948 VL= 67.196563 TS= 469.623362 D= 29.11241 DMAS= 0.284680E-10
FL= .000004291 VL= 66.439895 TS= 469.647344 D= 39.25370 DMAS= 0.697853E-10
FL= .000001737 VL= 65.647418 TS= 469.670345 D= 49.32203 DMAS= 0.138435E-09
FL= .000000175 VL= 64.854147 TS= 469.704798 D= 59.35721 DMAS= 0.241292E-09
FL= .000000018 VL= 63.328825 TS= 469.934194 D= 79.37990 DMAS= 0.577104E-09
FL= .000000002 VL= 61.919974 TS= 470.507689 D= 99.37627 DMAS= 0.113232E-08

X= 9.501321 YDUCT= 11.599271 MG= .067413 PO= 2075.6260 TO= 474.900205
DX= .007000000 A(X)= 422.6796 A(X)/A0= .55385 REL HUM. %= 29.490125

CV= .000555331 VG= 72.313731 TG= 474.462261 P= 2069.01 FLtot= .000126221
FL= .000011042 VL= 72.206573 TS= 469.539345 D= 7.39541 DMAS= 0.466669E-12
FL= .000044725 VL= 71.976138 TS= 469.552296 D= 13.34594 DMAS= 0.274265E-11
FL= .000039379 VL= 71.676709 TS= 469.566219 D= 18.73585 DMAS= 0.758827E-11
FL= .000024864 VL= 70.935815 TS= 469.594495 D= 29.07977 DMAS= 0.283723E-10
FL= .000004282 VL= 70.093559 TS= 469.621061 D= 39.22689 DMAS= 0.696425E-10
FL= .000001735 VL= 69.219370 TS= 469.645841 D= 49.29855 DMAS= 0.138237E-09
FL= .000000175 VL= 68.350304 TS= 469.678190 D= 59.33587 DMAS= 0.241032E-09
FL= .000000018 VL= 66.690963 TS= 469.875054 D= 79.36098 DMAS= 0.576691E-09
FL= .000000002 VL= 65.167229 TS= 470.383313 D= 99.35832 DMAS= 0.113171E-08

X= 10.005321 YDUCT= 11.270093 MG= .071433 PO= 2075.6260 TO= 474.893815
DX= .007000000 A(X)= 399.0294 A(X)/A0= .52286 REL HUM. %= 29.630342

CV= .000556731 VG= 76.620454 TG= 474.402152 P= 2068.20 FLtot= .000124819

FL=	.000010596	VL=	76.499938	TS=	469.498594	D=	7.29449	DMASS=	0.447825E-12
FL=	.000044138	VL=	76.234897	TS=	469.513305	D=	13.28733	DMASS=	0.270667E-11
FL=	.000039102	VL=	75.892717	TS=	469.529057	D=	18.69183	DMASS=	0.753491E-11
FL=	.000024783	VL=	75.054942	TS=	469.560828	D=	29.04812	DMASS=	0.282798E-10
FL=	.000004273	VL=	74.114243	TS=	469.590462	D=	39.20080	DMASS=	0.695036E-10
FL=	.000001732	VL=	73.147254	TS=	469.617583	D=	49.27562	DMASS=	0.138044E-09
FL=	.000000175	VL=	72.192784	TS=	469.649278	D=	59.31499	DMASS=	0.240777E-09
FL=	.000000018	VL=	70.383401	TS=	469.820869	D=	79.34243	DMASS=	0.576287E-09
FL=	.000000002	VL=	68.731778	TS=	470.272708	D=	99.34077	DMASS=	0.113111E-08
X=	10.502321	YDUCT=	10.945054	MG=	.075767	PO=	2075.6260	TO=	474.887900
DX=	.007000000	A(X)=	376.3446	A(X)/AO=	.49314	REL HUM. %=		29.773230	
CV=	.000558028	VG=	81.264172	TG=	474.334833	P=	2067.27	FLtot=	.000123521
FL=	.000010188	VL=	81.128130	TS=	469.451911	D=	7.19953	DMASS=	0.430562E-12
FL=	.000043594	VL=	80.822498	TS=	469.468726	D=	13.23246	DMASS=	0.267328E-11
FL=	.000038844	VL=	80.430656	TS=	469.486647	D=	18.65055	DMASS=	0.748510E-11
FL=	.000024707	VL=	79.482034	TS=	469.522519	D=	29.01830	DMASS=	0.281928E-10
FL=	.000004265	VL=	78.430577	TS=	469.555719	D=	39.17612	DMASS=	0.693724E-10
FL=	.000001730	VL=	77.360421	TS=	469.585697	D=	49.25387	DMASS=	0.137862E-09
FL=	.000000175	VL=	76.311758	TS=	469.617924	D=	59.29512	DMASS=	0.240536E-09
FL=	.000000018	VL=	74.338012	TS=	469.770792	D=	79.32476	DMASS=	0.575902E-09
FL=	.000000002	VL=	72.547057	TS=	470.175393	D=	99.32407	DMASS=	0.113054E-08
X=	11.006321	YDUCT=	10.615443	MG=	.080582	PO=	2075.6259	TO=	474.882279
DX=	.007000000	A(X)=	354.0186	A(X)/AO=	.46388	REL HUM. %=		29.924874	
CV=	.000559262	VG=	86.420950	TG=	474.256790	P=	2066.18	FLtot=	.000122286
FL=	.000009803	VL=	86.266514	TS=	469.396746	D=	7.10786	DMASS=	0.414324E-12
FL=	.000043075	VL=	85.912471	TS=	469.416136	D=	13.17974	DMASS=	0.264146E-11
FL=	.000038596	VL=	85.462050	TS=	469.436702	D=	18.61082	DMASS=	0.743736E-11
FL=	.000024633	VL=	84.384600	TS=	469.477544	D=	28.98945	DMASS=	0.281088E-10
FL=	.000004257	VL=	83.206129	TS=	469.515030	D=	39.15213	DMASS=	0.692451E-10
FL=	.000001728	VL=	82.018637	TS=	469.548520	D=	49.23266	DMASS=	0.137684E-09
FL=	.000000175	VL=	80.863395	TS=	469.582319	D=	59.27570	DMASS=	0.240299E-09
FL=	.000000018	VL=	78.704480	TS=	469.721410	D=	79.30745	DMASS=	0.575525E-09
FL=	.000000002	VL=	76.757092	TS=	470.085576	D=	99.30771	DMASS=	0.112998E-08
X=	11.503321	YDUCT=	10.290903	MG=	.085789	PO=	2075.6259	TO=	474.877091
DX=	.007000000	A(X)=	332.7031	A(X)/AO=	.43595	REL HUM. %=		30.083472	
CV=	.000560401	VG=	91.997002	TG=	474.168279	P=	2064.92	FLtot=	.000121146
FL=	.000009453	VL=	91.821077	TS=	469.333190	D=	7.02203	DMASS=	0.399494E-12
FL=	.000042594	VL=	91.410615	TS=	469.355663	D=	13.13058	DMASS=	0.261201E-11
FL=	.000038365	VL=	90.892863	TS=	469.379371	D=	18.57368	DMASS=	0.739292E-11
FL=	.000024564	VL=	89.669969	TS=	469.426077	D=	28.96233	DMASS=	0.280300E-10
FL=	.000004250	VL=	88.350422	TS=	469.468585	D=	39.12948	DMASS=	0.691249E-10
FL=	.000001726	VL=	87.033757	TS=	469.506233	D=	49.21255	DMASS=	0.137515E-09
FL=	.000000174	VL=	85.761720	TS=	469.542525	D=	59.25726	DMASS=	0.240075E-09
FL=	.000000018	VL=	83.400509	TS=	469.672389	D=	79.29096	DMASS=	0.575166E-09
FL=	.000000002	VL=	81.282528	TS=	470.003185	D=	99.29213	DMASS=	0.112945E-08
X=	12.000321	YDUCT=	9.966362	MG=	.091523	PO=	2075.6258	TO=	474.872242

DX=	.007000000	A(X)=	312.0493	A(X)/A0=	.40889	REL HUM. %=	30.254311
CV=	.000561467	VG=	98.135393	TG=	474.065679	P=	2063.45
FL=	.000009128	VL=	97.933485	TS=	469.258586	D=	6.94071
FL=	.000042144	VL=	97.454776	TS=	469.284888	D=	13.08415
FL=	.000038148	VL=	96.856745	TS=	469.312441	D=	18.53851
FL=	.000024498	VL=	95.464082	TS=	469.366212	D=	28.93650
FL=	.000004243	VL=	93.983409	TS=	469.414714	D=	39.10780
FL=	.000001724	VL=	92.521148	TS=	469.457336	D=	49.19324
FL=	.000000174	VL=	91.118424	TS=	469.497059	D=	59.23949
FL=	.000000018	VL=	88.532009	TS=	469.621473	D=	79.27503
FL=	.000000002	VL=	86.224699	TS=	469.924649	D=	99.27708
X=	12.504321	YDUCT=	9.636871	MG=	.097960	PO=	2075.6258
DX=	.007000000	A(X)=	291.7575	A(X)/A0=	.38230	REL HUM. %=	30.444221
CV=	.000562477	VG=	105.024232	TG=	473.943876	P=	2061.68
FL=	.000008824	VL=	104.790253	TS=	469.169100	D=	6.86286
FL=	.000041717	VL=	104.227513	TS=	469.200274	D=	13.03980
FL=	.000037940	VL=	103.532143	TS=	469.232663	D=	18.50480
FL=	.000024435	VL=	101.937660	TS=	469.295183	D=	28.91157
FL=	.000004236	VL=	100.268955	TS=	469.351011	D=	39.08678
FL=	.000001722	VL=	98.638723	TS=	469.399694	D=	49.17445
FL=	.000000174	VL=	97.086275	TS=	469.443921	D=	59.22215
FL=	.000000018	VL=	94.243285	TS=	469.566316	D=	79.25944
FL=	.000000002	VL=	91.721116	TS=	469.846773	D=	99.26235
X=	13.001321	YDUCT=	9.311708	MG=	.105011	PO=	2075.6256
DX=	.007000000	A(X)=	272.4009	A(X)/A0=	.35694	REL HUM. %=	30.652955
CV=	.000563405	VG=	112.567177	TG=	473.802201	P=	2059.61
FL=	.000008548	VL=	112.294775	TS=	469.064146	D=	6.79061
FL=	.000041324	VL=	111.631739	TS=	469.101375	D=	12.99871
FL=	.000037748	VL=	110.822154	TS=	469.139704	D=	18.47344
FL=	.000024376	VL=	108.995527	TS=	469.212831	D=	28.88821
FL=	.000004230	VL=	107.114033	TS=	469.277429	D=	39.06698
FL=	.000001720	VL=	105.295364	TS=	469.333324	D=	49.15668
FL=	.000000174	VL=	103.575766	TS=	469.383134	D=	59.20571
FL=	.000000018	VL=	100.447451	TS=	469.506822	D=	79.24460
FL=	.000000002	VL=	97.687045	TS=	469.769666	D=	99.24831
X=	13.505321	YDUCT=	8.981587	MG=	.112990	PO=	2075.6255
DX=	.007000000	A(X)=	253.4289	A(X)/A0=	.33208	REL HUM. %=	30.893134
CV=	.000564280	VG=	121.098865	TG=	473.631267	P=	2057.10
FL=	.000008292	VL=	120.778548	TS=	468.936708	D=	6.72194
FL=	.000040952	VL=	119.991115	TS=	468.981780	D=	12.95964
FL=	.000037564	VL=	119.042499	TS=	469.027682	D=	18.44351
FL=	.000024319	VL=	116.939564	TS=	469.114129	D=	28.86574
FL=	.000004223	VL=	114.809509	TS=	469.189596	D=	39.04782
FL=	.000001718	VL=	112.772781	TS=	469.254366	D=	49.13943
FL=	.000000174	VL=	110.860628	TS=	469.311194	D=	59.18970
FL=	.000000018	VL=	107.404828	TS=	469.439512		

FL=	.000000002	VL=	104.371604	TS=	469.689052	D=	99.23457	DMASS=	0.112749E-08
X=	14.002321	YDUCT=	8.656054	MG=	.121799	PO=	2075.6253	TO=	474.855893
DX=	.007000000	A(X)=	235.3910	A(X)/AO=	.30844	REL HUM. %=		31.166416	
CV=	.000565081	VG=	130.512927	TG=	473.429259	P=	2054.12	FLtot=	.000116460
FL=	.000008060	VL=	130.134563	TS=	468.785363	D=	6.65871	DMASS=	0.340638E-12
FL=	.000040612	VL=	129.197538	TS=	468.840361	D=	12.92364	DMASS=	0.249045E-11
FL=	.000037395	VL=	128.085122	TS=	468.895703	D=	18.41579	DMASS=	0.720598E-11
FL=	.000024266	VL=	125.663654	TS=	468.998511	D=	28.84475	DMASS=	0.276900E-10
FL=	.000004218	VL=	123.251695	TS=	469.087155	D=	39.02982	DMASS=	0.685981E-10
FL=	.000001716	VL=	120.969544	TS=	469.162594	D=	49.12314	DMASS=	0.136767E-09
FL=	.000000174	VL=	118.841540	TS=	469.227947	D=	59.17454	DMASS=	0.239071E-09
FL=	.000000018	VL=	115.019278	TS=	469.364253	D=	79.21631	DMASS=	0.573544E-09
FL=	.000000002	VL=	111.681330	TS=	469.605009	D=	99.22149	DMASS=	0.112704E-08
X=	14.506321	YDUCT=	8.326501	MG=	.131832	PO=	2075.6251	TO=	474.852532
DX=	.007000000	A(X)=	217.8086	A(X)/AO=	.28540	REL HUM. %=		31.491470	
CV=	.000565833	VG=	141.227373	TG=	473.182016	P=	2050.46	FLtot=	.000115708
FL=	.000007846	VL=	140.775951	TS=	468.599483	D=	6.59912	DMASS=	0.331575E-12
FL=	.000040292	VL=	139.653201	TS=	468.667495	D=	12.88964	DMASS=	0.247084E-11
FL=	.000037235	VL=	138.342204	TS=	468.735001	D=	18.38945	DMASS=	0.717511E-11
FL=	.000024215	VL=	135.543628	TS=	468.858572	D=	28.82463	DMASS=	0.276321E-10
FL=	.000004212	VL=	132.803421	TS=	468.963721	D=	39.01246	DMASS=	0.685066E-10
FL=	.000001715	VL=	130.237467	TS=	469.052408	D=	49.10737	DMASS=	0.136635E-09
FL=	.000000174	VL=	127.860529	TS=	469.128387	D=	59.15981	DMASS=	0.238893E-09
FL=	.000000018	VL=	123.616413	TS=	469.276570	D=	79.20286	DMASS=	0.573251E-09
FL=	.000000002	VL=	119.927944	TS=	469.512788	D=	99.20870	DMASS=	0.112661E-08
X=	15.003321	YDUCT=	8.001397	MG=	.143026	PO=	2075.6247	TO=	474.849502
DX=	.007000000	A(X)=	201.1322	A(X)/AO=	.26355	REL HUM. %=		31.874972	
CV=	.000566517	VG=	153.171608	TG=	472.884430	P=	2046.04	FLtot=	.000115023
FL=	.000007653	VL=	152.627915	TS=	468.375367	D=	6.54480	DMASS=	0.323453E-12
FL=	.000040001	VL=	151.274671	TS=	468.460391	D=	12.85852	DMASS=	0.245299E-11
FL=	.000037088	VL=	149.723709	TS=	468.543389	D=	18.36519	DMASS=	0.714675E-11
FL=	.000024168	VL=	146.482162	TS=	468.692856	D=	28.80592	DMASS=	0.275783E-10
FL=	.000004207	VL=	143.364645	TS=	468.818269	D=	38.99621	DMASS=	0.684210E-10
FL=	.000001713	VL=	140.475721	TS=	468.923059	D=	49.09253	DMASS=	0.136511E-09
FL=	.000000173	VL=	137.816848	TS=	469.011941	D=	59.14591	DMASS=	0.238724E-09
FL=	.000000018	VL=	133.096509	TS=	469.176075	D=	79.19011	DMASS=	0.572975E-09
FL=	.000000002	VL=	129.013222	TS=	469.412258	D=	99.19655	DMASS=	0.112619E-08
X=	15.500321	YDUCT=	7.675488	MG=	.155785	PO=	2075.6243	TO=	474.846753
DX=	.007000000	A(X)=	185.0810	A(X)/AO=	.24252	REL HUM. %=		32.342914	
CV=	.000567145	VG=	166.771847	TG=	472.517168	P=	2040.59	FLtot=	.000114394
FL=	.000007479	VL=	166.109239	TS=	468.098601	D=	6.49485	DMASS=	0.316103E-12
FL=	.000039733	VL=	164.464064	TS=	468.206515	D=	12.82973	DMASS=	0.243655E-11
FL=	.000036951	VL=	162.617366	TS=	468.309819	D=	18.34258	DMASS=	0.712039E-11
FL=	.000024124	VL=	158.843766	TS=	468.492449	D=	28.78829	DMASS=	0.275277E-10
FL=	.000004202	VL=	155.281352	TS=	468.643335	D=	38.98079	DMASS=	0.683399E-10

FL=	.000001712	VL=	152.014994	TS=	468.768138	D=	49.07840	DMASS=	0.136393E-09
FL=	.000000173	VL=	149.028242	TS=	468.872985	D=	59.13261	DMASS=	0.238563E-09
FL=	.000000018	VL=	143.756302	TS=	469.058062	D=	79.17786	DMASS=	0.572709E-09
FL=	.000000002	VL=	139.217263	TS=	469.298945	D=	99.18485	DMASS=	0.112579E-08
X=	16.004321	YDUCT=	7.344689	MG=	.170628	PO=	2075.6238	TO=	474.844258
DX=	.007000000	A(X)=	169.4715	A(X)/A0=	.22206	REL HUM. %		32.933757	
CV=	.000567729	VG=	182.572581	TG=	472.052238	P=	2033.69	FLtot=	.000113809
FL=	.000007321	VL=	181.752410	TS=	467.748268	D=	6.44864	DMASS=	0.309404E-12
FL=	.000039484	VL=	179.735052	TS=	467.887591	D=	12.80290	DMASS=	0.242129E-11
FL=	.000036823	VL=	177.522391	TS=	468.018124	D=	18.32133	DMASS=	0.709567E-11
FL=	.000024082	VL=	173.105261	TS=	468.244297	D=	28.77152	DMASS=	0.274796E-10
FL=	.000004197	VL=	169.011614	TS=	468.428011	D=	38.96602	DMASS=	0.682622E-10
FL=	.000001710	VL=	165.296741	TS=	468.578289	D=	49.06477	DMASS=	0.136280E-09
FL=	.000000173	VL=	161.921286	TS=	468.703333	D=	59.11975	DMASS=	0.238408E-09
FL=	.000000018	VL=	155.996841	TS=	468.915857	D=	79.16593	DMASS=	0.572450E-09
FL=	.000000002	VL=	150.919927	TS=	469.166907	D=	99.17343	DMASS=	0.112540E-08
X=	16.501321	YDUCT=	7.013268	MG=	.187825	PO=	2075.6230	TO=	474.842102
DX=	.007000000	A(X)=	154.5222	A(X)/A0=	.20248	REL HUM. %		33.687114	
CV=	.000568253	VG=	200.850106	TG=	471.462934	P=	2024.95	FLtot=	.000113285
FL=	.000007182	VL=	199.820947	TS=	467.305311	D=	6.40744	DMASS=	0.303512E-12
FL=	.000039261	VL=	197.304943	TS=	467.489592	D=	12.77869	DMASS=	0.240759E-11
FL=	.000036706	VL=	194.613782	TS=	467.657278	D=	18.30196	DMASS=	0.707319E-11
FL=	.000024043	VL=	189.383626	TS=	467.940777	D=	28.75604	DMASS=	0.274353E-10
FL=	.000004193	VL=	184.638259	TS=	468.166585	D=	38.95226	DMASS=	0.681900E-10
FL=	.000001709	VL=	180.381404	TS=	468.349016	D=	49.05201	DMASS=	0.136174E-09
FL=	.000000173	VL=	176.540362	TS=	468.499311	D=	59.10765	DMASS=	0.238261E-09
FL=	.000000018	VL=	169.840584	TS=	468.746810	D=	79.15466	DMASS=	0.572205E-09
FL=	.000000002	VL=	164.129202	TS=	469.014199	D=	99.16259	DMASS=	0.112504E-08
X=	17.005321	YDUCT=	6.688209	MG=	.207484	PO=	2075.6220	TO=	474.840250
DX=	.007000000	A(X)=	140.5302	A(X)/A0=	.18414	REL HUM. %		34.649761	
CV=	.000568731	VG=	221.700256	TG=	470.722869	P=	2014.00	FLtot=	.000112806
FL=	.000007057	VL=	220.460186	TS=	466.745013	D=	6.37013	DMASS=	0.298241E-12
FL=	.000039057	VL=	217.443227	TS=	466.985496	D=	12.75650	DMASS=	0.239507E-11
FL=	.000036598	VL=	214.268247	TS=	467.201479	D=	18.28401	DMASS=	0.705240E-11
FL=	.000024006	VL=	208.183158	TS=	467.559911	D=	28.74146	DMASS=	0.273936E-10
FL=	.000004188	VL=	202.721692	TS=	467.840293	D=	38.93919	DMASS=	0.681213E-10
FL=	.000001708	VL=	197.853740	TS=	468.064036	D=	49.03981	DMASS=	0.136072E-09
FL=	.000000173	VL=	193.479612	TS=	468.246571	D=	59.09602	DMASS=	0.238121E-09
FL=	.000000018	VL=	185.880850	TS=	468.539233	D=	79.14375	DMASS=	0.571969E-09
FL=	.000000002	VL=	179.427240	TS=	468.830612	D=	99.15206	DMASS=	0.112468E-08
X=	17.502321	YDUCT=	6.389047	MG=	.228617	PO=	2075.6208	TO=	474.838774
DX=	.007000000	A(X)=	128.2396	A(X)/A0=	.16804	REL HUM. %		35.817838	
CV=	.000569152	VG=	244.057328	TG=	469.848785	P=	2001.11	FLtot=	.000112385
FL=	.000006949	VL=	242.623047	TS=	466.078372	D=	6.33759	DMASS=	0.293694E-12
FL=	.000038877	VL=	239.132672	TS=	466.383876	D=	12.73691	DMASS=	0.238405E-11

FL=	.000036502	VL=	235.499305	TS=	466.656802	D=	18.26800	DMASS=	0.703388E-11
FL=	.000023973	VL=	228.600203	TS=	467.105287	D=	28.72827	DMASS=	0.273559E-10
FL=	.000004184	VL=	222.442613	TS=	467.451686	D=	38.92723	DMASS=	0.680586E-10
FL=	.000001707	VL=	216.966321	TS=	467.725345	D=	49.02856	DMASS=	0.135978E-09
FL=	.000000173	VL=	212.050872	TS=	467.946751	D=	59.08525	DMASS=	0.237991E-09
FL=	.000000018	VL=	203.519530	TS=	468.294334	D=	79.13355	DMASS=	0.571748E-09
FL=	.000000002	VL=	196.280650	TS=	468.617220	D=	99.14217	DMASS=	0.112434E-08
X=	18.006321	YDUCT=	6.119458	MG=	.250773	PO=	2075.6193	TO=	474.837634
DX=	.007000000	A(X)=	117.6456	A(X)/AO=	.15415	REL HUM. %			37.206558
CV=	.000569530	VG=	267.428136	TG=	468.845780	P=	1986.38	Fltot=	.000112006
FL=	.000006854	VL=	265.883795	TS=	465.302396	D=	6.30862	DMASS=	0.289685E-12
FL=	.000038716	VL=	262.048391	TS=	465.676464	D=	12.71929	DMASS=	0.237416E-11
FL=	.000036415	VL=	258.053838	TS=	466.012931	D=	18.25344	DMASS=	0.701708E-11
FL=	.000023943	VL=	250.469750	TS=	466.565527	D=	28.71609	DMASS=	0.273211E-10
FL=	.000004181	VL=	243.693906	TS=	466.989802	D=	38.91609	DMASS=	0.680002E-10
FL=	.000001705	VL=	237.657281	TS=	467.322746	D=	49.01801	DMASS=	0.135891E-09
FL=	.000000173	VL=	232.229416	TS=	467.590441	D=	59.07508	DMASS=	0.237868E-09
FL=	.000000018	VL=	222.788904	TS=	468.003980	D=	79.12386	DMASS=	0.571538E-09
FL=	.000000002	VL=	214.762531	TS=	468.366641	D=	99.13271	DMASS=	0.112402E-08
X=	18.503321	YDUCT=	5.908304	MG=	.270671	PO=	2075.6178	TO=	474.836798
DX=	.007000000	A(X)=	109.6669	A(X)/AO=	.14370	REL HUM. %			38.613365
CV=	.000569857	VG=	288.350870	TG=	467.870214	P=	1972.14	Fltot=	.000111679
FL=	.000006773	VL=	286.866538	TS=	464.523751	D=	6.28362	DMASS=	0.286254E-12
FL=	.000038577	VL=	283.120252	TS=	464.939485	D=	12.70402	DMASS=	0.236562E-11
FL=	.000036339	VL=	279.122789	TS=	465.329650	D=	18.24074	DMASS=	0.700245E-11
FL=	.000023916	VL=	271.340879	TS=	465.982514	D=	28.70534	DMASS=	0.272904E-10
FL=	.000004178	VL=	264.258092	TS=	466.486799	D=	38.90615	DMASS=	0.679481E-10
FL=	.000001704	VL=	257.880231	TS=	466.882280	D=	49.00852	DMASS=	0.135812E-09
FL=	.000000173	VL=	252.103812	TS=	467.199477	D=	59.06588	DMASS=	0.237757E-09
FL=	.000000018	VL=	241.983166	TS=	467.684611	D=	79.11500	DMASS=	0.571346E-09
FL=	.000000002	VL=	233.320455	TS=	468.092100	D=	99.12403	DMASS=	0.112372E-08
X=	19.000321	YDUCT=	5.732180	MG=	.289337	PO=	2075.6163	TO=	474.836211
DX=	.007000000	A(X)=	103.2261	A(X)/AO=	.13526	REL HUM. %			40.082880
CV=	.000570147	VG=	307.917831	TG=	466.891512	P=	1957.91	Fltot=	.000111389
FL=	.000006702	VL=	306.440636	TS=	463.743707	D=	6.26146	DMASS=	0.283237E-12
FL=	.000038453	VL=	302.680767	TS=	464.194523	D=	12.69049	DMASS=	0.235807E-11
FL=	.000036272	VL=	298.667275	TS=	464.628757	D=	18.22945	DMASS=	0.698946E-11
FL=	.000023892	VL=	290.819140	TS=	465.373377	D=	28.69571	DMASS=	0.272630E-10
FL=	.000004175	VL=	283.605305	TS=	465.956066	D=	38.89718	DMASS=	0.679011E-10
FL=	.000001704	VL=	277.050106	TS=	466.414744	D=	48.99991	DMASS=	0.135740E-09
FL=	.000000173	VL=	271.068647	TS=	466.782811	D=	59.05748	DMASS=	0.237655E-09
FL=	.000000018	VL=	260.499297	TS=	467.342727	D=	79.10686	DMASS=	0.571169E-09
FL=	.000000002	VL=	251.374935	TS=	467.798430	D=	99.11599	DMASS=	0.112345E-08
X=	19.504321	YDUCT=	5.578275	MG=	.307476	PO=	2075.6147	TO=	474.835847
DX=	.007000000	A(X)=	97.7574	A(X)/AO=	.12809	REL HUM. %			41.662366

CV=	.000570409	VG=	326.872929	TG=	465.882261	P=	1943.32	FLtot=	.000111127
FL=	.000006638	VL=	325.375638	TS=	462.938409	D=	6.24143	DMASS=	0.280528E-12
FL=	.000038342	VL=	321.549204	TS=	463.427030	D=	12.67823	DMASS=	0.235125E-11
FL=	.000036210	VL=	317.477972	TS=	463.902375	D=	18.21920	DMASS=	0.697767E-11
FL=	.000023870	VL=	309.533645	TS=	464.734291	D=	28.68689	DMASS=	0.272378E-10
FL=	.000004172	VL=	302.215636	TS=	465.394954	D=	38.88891	DMASS=	0.678578E-10
FL=	.000001703	VL=	295.535379	TS=	465.918053	D=	48.99193	DMASS=	0.135674E-09
FL=	.000000173	VL=	289.409836	TS=	466.338709	D=	59.04968	DMASS=	0.237561E-09
FL=	.000000017	VL=	278.513863	TS=	466.976975	D=	79.09924	DMASS=	0.571004E-09
FL=	.000000002	VL=	269.036693	TS=	467.484343	D=	99.10844	DMASS=	0.112319E-08

X=	20.001321	YDUCT=	5.446888	MG=	.324540	PO=	2075.6131	TO=	474.835691
DX=	.007000000	A(X)=	93.2066	A(X)/A0=	.12213	REL HUM. %=			43.296958

CV=	.000570640	VG=	344.647004	TG=	464.881197	P=	1928.92	FLtot=	.000110895
FL=	.000006581	VL=	343.141669	TS=	462.133872	D=	6.22378	DMASS=	0.278153E-12
FL=	.000038244	VL=	339.282644	TS=	462.658555	D=	12.66740	DMASS=	0.234523E-11
FL=	.000036156	VL=	335.173637	TS=	463.172624	D=	18.21009	DMASS=	0.696721E-11
FL=	.000023850	VL=	327.145356	TS=	464.086415	D=	28.67900	DMASS=	0.272154E-10
FL=	.000004170	VL=	319.737493	TS=	464.822416	D=	38.88147	DMASS=	0.678189E-10
FL=	.000001702	VL=	312.957358	TS=	465.409092	D=	48.98471	DMASS=	0.135614E-09
FL=	.000000172	VL=	306.720605	TS=	465.882321	D=	59.04258	DMASS=	0.237475E-09
FL=	.000000017	VL=	295.573781	TS=	466.599871	D=	79.09227	DMASS=	0.570853E-09
FL=	.000000002	VL=	285.820963	TS=	467.160498	D=	99.10150	DMASS=	0.112296E-08

X=	20.505321	YDUCT=	5.327000	MG=	.341579	PO=	2075.6115	TO=	474.835746
DX=	.007000000	A(X)=	89.1487	A(X)/A0=	.11681	REL HUM. %=			45.085722

CV=	.000570851	VG=	362.337846	TG=	463.832264	P=	1913.92	FLtot=	.000110684
FL=	.000006531	VL=	360.783520	TS=	461.292844	D=	6.20772	DMASS=	0.276006E-12
FL=	.000038154	VL=	356.801219	TS=	461.860413	D=	12.65752	DMASS=	0.233974E-11
FL=	.000036106	VL=	352.594825	TS=	462.415129	D=	18.20175	DMASS=	0.695764E-11
FL=	.000023832	VL=	344.423632	TS=	463.410879	D=	28.67171	DMASS=	0.271946E-10
FL=	.000004167	VL=	336.900861	TS=	464.222691	D=	38.87456	DMASS=	0.677827E-10
FL=	.000001701	VL=	330.013094	TS=	464.874212	D=	48.97796	DMASS=	0.135558E-09
FL=	.000000172	VL=	323.668045	TS=	465.401590	D=	59.03592	DMASS=	0.237395E-09
FL=	.000000017	VL=	312.293751	TS=	466.201613	D=	79.08568	DMASS=	0.570711E-09
FL=	.000000002	VL=	302.299060	TS=	466.818481	D=	99.09492	DMASS=	0.112273E-08

X=	21.002321	YDUCT=	5.220702	MG=	.358035	PO=	2075.6097	TO=	474.836000
DX=	.007000000	A(X)=	85.6264	A(X)/A0=	.11220	REL HUM. %=			46.975415

CV=	.000571038	VG=	379.366509	TG=	462.773049	P=	1898.85	FLtot=	.000110497
FL=	.000006486	VL=	377.776564	TS=	460.437798	D=	6.19355	DMASS=	0.274120E-12
FL=	.000038075	VL=	373.700799	TS=	461.050166	D=	12.64874	DMASS=	0.233488E-11
FL=	.000036062	VL=	369.403044	TS=	461.647165	D=	18.19430	DMASS=	0.694910E-11
FL=	.000023816	VL=	361.071509	TS=	462.724613	D=	28.66514	DMASS=	0.271760E-10
FL=	.000004165	VL=	353.415183	TS=	463.611494	D=	38.86828	DMASS=	0.677498E-10
FL=	.000001701	VL=	346.408234	TS=	464.327729	D=	48.97180	DMASS=	0.135507E-09
FL=	.000000172	VL=	339.950290	TS=	464.909537	D=	59.02981	DMASS=	0.237321E-09
FL=	.000000017	VL=	328.354525	TS=	465.793127	D=	79.07961	DMASS=	0.570579E-09
FL=	.000000002	VL=	318.136100	TS=	466.467697	D=	99.08882	DMASS=	0.112253E-08

X=	21.506321	YDUCT=	5.121473	MG=	.374708	PO=	2075.6078	TO=	474.836475
DX=	.007000000	A(X)=	82.4024	A(X)/AO=	.10797	REL HUM. %=		49.067156	
CV=	.000571209	VG=	396.559489	TG=	461.654303	P=	1883.03	FLtot=	.000110326
FL=	.000006446	VL=	394.906419	TS=	459.534921	D=	6.18069	DMASS=	0.272417E-12
FL=	.000038003	VL=	390.676353	TS=	460.199223	D=	12.64072	DMASS=	0.233044E-11
FL=	.000036021	VL=	386.248386	TS=	460.842717	D=	18.18745	DMASS=	0.694126E-11
FL=	.000023800	VL=	377.711926	TS=	462.005941	D=	28.65905	DMASS=	0.271586E-10
FL=	.000004164	VL=	369.893140	TS=	462.970247	D=	38.86240	DMASS=	0.677191E-10
FL=	.000001700	VL=	362.746637	TS=	463.753349	D=	48.96600	DMASS=	0.135459E-09
FL=	.000000172	VL=	356.161830	TS=	464.391651	D=	59.02403	DMASS=	0.237252E-09
FL=	.000000017	VL=	344.330495	TS=	465.362501	D=	79.07382	DMASS=	0.570454E-09
FL=	.000000002	VL=	333.886206	TS=	466.097939	D=	99.08298	DMASS=	0.112233E-08
X=	22.003321	YDUCT=	5.031572	MG=	.391063	PO=	2075.6058	TO=	474.837157
DX=	.007000000	A(X)=	79.5348	A(X)/AO=	.10422	REL HUM. %=		51.308398	
CV=	.000571360	VG=	413.362434	TG=	460.513047	P=	1866.98	FLtot=	.000110174
FL=	.000006411	VL=	411.656402	TS=	458.608176	D=	6.16941	DMASS=	0.270928E-12
FL=	.000037939	VL=	407.293095	TS=	459.327477	D=	12.63363	DMASS=	0.232652E-11
FL=	.000035985	VL=	402.738064	TS=	460.020540	D=	18.18134	DMASS=	0.693426E-11
FL=	.000023787	VL=	393.982919	TS=	461.272392	D=	28.65354	DMASS=	0.271430E-10
FL=	.000004162	VL=	385.984684	TS=	462.315114	D=	38.85705	DMASS=	0.676911E-10
FL=	.000001699	VL=	378.684031	TS=	463.165814	D=	48.96068	DMASS=	0.135414E-09
FL=	.000000172	VL=	371.961090	TS=	463.861357	D=	59.01871	DMASS=	0.237187E-09
FL=	.000000017	VL=	359.880976	TS=	464.921009	D=	79.06845	DMASS=	0.570338E-09
FL=	.000000002	VL=	349.207206	TS=	465.718910	D=	99.07754	DMASS=	0.112214E-08
X=	22.500321	YDUCT=	4.947965	MG=	.407486	PO=	2075.6036	TO=	474.838065
DX=	.007000000	A(X)=	76.9136	A(X)/AO=	.10078	REL HUM. %=		53.765953	
CV=	.000571496	VG=	430.173288	TG=	459.323867	P=	1850.36	FLtot=	.000110038
FL=	.000006379	VL=	428.401364	TS=	457.640377	D=	6.15941	DMASS=	0.269613E-12
FL=	.000037882	VL=	423.875246	TS=	458.420101	D=	12.62727	DMASS=	0.232301E-11
FL=	.000035952	VL=	419.175853	TS=	459.166799	D=	18.17582	DMASS=	0.692795E-11
FL=	.000023774	VL=	410.181129	TS=	460.512217	D=	28.64850	DMASS=	0.271286E-10
FL=	.000004160	VL=	401.986896	TS=	461.636044	D=	38.85210	DMASS=	0.676653E-10
FL=	.000001699	VL=	394.517887	TS=	462.556339	D=	48.95572	DMASS=	0.135373E-09
FL=	.000000172	VL=	387.644931	TS=	463.310847	D=	59.01372	DMASS=	0.237127E-09
FL=	.000000017	VL=	375.298951	TS=	464.462244	D=	79.06337	DMASS=	0.570228E-09
FL=	.000000002	VL=	364.386013	TS=	465.325116	D=	99.07237	DMASS=	0.112197E-08
X=	23.004321	YDUCT=	4.869482	MG=	.424115	PO=	2075.6012	TO=	474.839217
DX=	.007000000	A(X)=	74.4930	A(X)/AO=	.09761	REL HUM. %=		56.486223	
CV=	.000571619	VG=	447.128125	TG=	458.076477	P=	1833.05	FLtot=	.000109915
FL=	.000006352	VL=	445.300955	TS=	456.618367	D=	6.15050	DMASS=	0.268444E-12
FL=	.000037830	VL=	440.632784	TS=	457.462472	D=	12.62153	DMASS=	0.231984E-11
FL=	.000035923	VL=	435.795347	TS=	458.267260	D=	18.17079	DMASS=	0.692219E-11
FL=	.000023763	VL=	426.556897	TS=	459.712825	D=	28.64383	DMASS=	0.271154E-10
FL=	.000004159	VL=	418.156635	TS=	460.922019	D=	38.84746	DMASS=	0.676411E-10
FL=	.000001698	VL=	410.508220	TS=	461.915167	D=	48.95105	DMASS=	0.135334E-09
FL=	.000000172	VL=	403.474679	TS=	462.731370	D=	59.00898	DMASS=	0.237070E-09

FL=	.000000017	VL=	390.845058	TS=	463.978953	D=	79.05852	DMASS=	0.570123E-09
FL=	.000000002	VL=	379.680091	TS=	464.910324	D=	99.06740	DMASS=	0.112180E-08
X=	23.501321	YDUCT=	4.797625	MG=	.440513	PO=	2075.5987	TO=	474.840588
DX=	.007000000	A(X)=	72.3107	A(X)/A0=	.09475	REL HUM. %=		59.419912	
CV=	.000571726	VG=	463.778974	TG=	456.804494	P=	1815.51	FLtot=	.000109808
FL=	.00006328	VL=	461.897403	TS=	455.571195	D=	6.14283	DMASS=	0.267441E-12
FL=	.000037785	VL=	457.088044	TS=	456.481686	D=	12.61653	DMASS=	0.231708E-11
FL=	.000035896	VL=	452.117406	TS=	457.346909	D=	18.16634	DMASS=	0.691712E-11
FL=	.000023752	VL=	442.643536	TS=	458.896231	D=	28.63964	DMASS=	0.271035E-10
FL=	.000004157	VL=	434.040492	TS=	460.192779	D=	38.84325	DMASS=	0.676191E-10
FL=	.000001698	VL=	426.212874	TS=	461.260083	D=	48.94676	DMASS=	0.135299E-09
FL=	.000000172	VL=	419.017513	TS=	462.139025	D=	59.00461	DMASS=	0.237017E-09
FL=	.000000017	VL=	406.100810	TS=	463.484561	D=	79.05399	DMASS=	0.570025E-09
FL=	.000000002	VL=	394.681395	TS=	464.486024	D=	99.06274	DMASS=	0.112164E-08
X=	24.005321	YDUCT=	4.730433	MG=	.457001	PO=	2075.5960	TO=	474.842206
DX=	.007000000	A(X)=	70.2994	A(X)/A0=	.09212	REL HUM. %=		62.647015	
CV=	.000571821	VG=	480.451022	TG=	455.484255	P=	1797.43	FLtot=	.000109712
FL=	.000006307	VL=	478.533401	TS=	454.475365	D=	6.13613	DMASS=	0.266566E-12
FL=	.000037745	VL=	473.617495	TS=	455.453259	D=	12.61207	DMASS=	0.231463E-11
FL=	.000035872	VL=	468.534033	TS=	456.381787	D=	18.16234	DMASS=	0.691254E-11
FL=	.000023742	VL=	458.845363	TS=	458.040510	D=	28.63578	DMASS=	0.270925E-10
FL=	.000004156	VL=	450.048515	TS=	459.428611	D=	38.83933	DMASS=	0.675986E-10
FL=	.000001698	VL=	442.045237	TS=	460.573336	D=	48.94272	DMASS=	0.135265E-09
FL=	.000000172	VL=	434.688749	TS=	461.517733	D=	59.00047	DMASS=	0.236968E-09
FL=	.000000017	VL=	421.482585	TS=	462.965591	D=	79.04965	DMASS=	0.569931E-09
FL=	.000000002	VL=	409.804932	TS=	464.040590	D=	99.05824	DMASS=	0.112149E-08
X=	24.502321	YDUCT=	4.669768	MG=	.472977	PO=	2075.5931	TO=	474.844009
DX=	.007000000	A(X)=	68.5079	A(X)/A0=	.08977	REL HUM. %=		66.066460	
CV=	.000571904	VG=	496.536600	TG=	454.166208	P=	1779.52	FLtot=	.000109630
FL=	.000006290	VL=	494.600586	TS=	453.371847	D=	6.13049	DMASS=	0.265832E-12
FL=	.000037711	VL=	489.621723	TS=	454.412926	D=	12.60826	DMASS=	0.231253E-11
FL=	.000035852	VL=	484.461146	TS=	455.403942	D=	18.15885	DMASS=	0.690856E-11
FL=	.000023734	VL=	474.605914	TS=	457.172821	D=	28.63235	DMASS=	0.270828E-10
FL=	.000004155	VL=	465.645348	TS=	458.653320	D=	38.83578	DMASS=	0.675801E-10
FL=	.000001697	VL=	457.486774	TS=	459.876109	D=	48.93904	DMASS=	0.135235E-09
FL=	.000000172	VL=	449.983763	TS=	460.886526	D=	58.99665	DMASS=	0.236922E-09
FL=	.000000017	VL=	436.507724	TS=	462.437787	D=	79.04562	DMASS=	0.569844E-09
FL=	.000000002	VL=	424.584813	TS=	463.587420	D=	99.05403	DMASS=	0.112134E-08
X=	25.006321	YDUCT=	4.613415	MG=	.488871	PO=	2075.5901	TO=	474.846040
DX=	.007000000	A(X)=	66.8644	A(X)/A0=	.08761	REL HUM. %=		69.783386	
CV=	.000571976	VG=	512.469992	TG=	452.817777	P=	1761.32	FLtot=	.000109558
FL=	.000006275	VL=	510.519128	TS=	452.235723	D=	6.12568	DMASS=	0.265208E-12
FL=	.000037681	VL=	505.491459	TS=	453.337700	D=	12.60493	DMASS=	0.231070E-11
FL=	.000035833	VL=	500.273626	TS=	454.391031	D=	18.15575	DMASS=	0.690502E-11
FL=	.000023726	VL=	490.289334	TS=	456.272441	D=	28.62922	DMASS=	0.270739E-10

FL=	.000004154	VL=	481.193185	TS=	457.848018	D=	38.83249	DMASS=	0.675629E-10
FL=	.000001697	VL=	472.899942	TS=	459.151232	D=	48.93558	DMASS=	0.135206E-09
FL=	.000000172	VL=	465.265806	TS=	460.229748	D=	58.99304	DMASS=	0.236878E-09
FL=	.000000017	VL=	451.540799	TS=	461.887910	D=	79.04176	DMASS=	0.569760E-09
FL=	.000000002	VL=	439.385907	TS=	463.115041	D=	99.04997	DMASS=	0.112121E-08
X=	25.503321	YDUCT=	4.562385	MG=	.504256	PO=	2075.5869	TO=	474.848238
DX=	.007000000	A(X)=	65.3934	A(X)/A0=	.08569	REL HUM. %=		73.711062	
CV=	.000572037	VG=	527.824901	TG=	451.477932	P=	1743.37	FLtot=	.000109497
FL=	.000006263	VL=	525.864809	TS=	451.100223	D=	6.12177	DMASS=	0.264699E-12
FL=	.000037656	VL=	520.794466	TS=	452.260668	D=	12.60214	DMASS=	0.230917E-11
FL=	.000035818	VL=	515.528131	TS=	453.374331	D=	18.15309	DMASS=	0.690199E-11
FL=	.000023719	VL=	505.438928	TS=	455.366898	D=	28.62646	DMASS=	0.270661E-10
FL=	.000004153	VL=	496.231318	TS=	457.037190	D=	38.82954	DMASS=	0.675475E-10
FL=	.000001697	VL=	487.824472	TS=	458.420685	D=	48.93244	DMASS=	0.135180E-09
FL=	.000000172	VL=	480.077145	TS=	459.567276	D=	58.98973	DMASS=	0.236838E-09
FL=	.000000017	VL=	466.131601	TS=	461.332551	D=	79.03817	DMASS=	0.569683E-09
FL=	.000000002	VL=	453.766310	TS=	462.637649	D=	99.04617	DMASS=	0.112108E-08
X=	26.000321	YDUCT=	4.516049	MG=	.519150	PO=	2075.5835	TO=	474.850590
DX=	.007000000	A(X)=	64.0718	A(X)/A0=	.08396	REL HUM. %=		77.854202	
CV=	.000572088	VG=	542.625527	TG=	450.148939	P=	1725.69	FLtot=	.000109445
FL=	.000006253	VL=	540.688006	TS=	449.961114	D=	6.11860	DMASS=	0.264289E-12
FL=	.000037635	VL=	535.636028	TS=	451.174105	D=	12.59980	DMASS=	0.230788E-11
FL=	.000035804	VL=	530.357230	TS=	452.345548	D=	18.15081	DMASS=	0.689939E-11
FL=	.000023713	VL=	520.206058	TS=	454.447817	D=	28.62401	DMASS=	0.270591E-10
FL=	.000004152	VL=	510.916602	TS=	456.212917	D=	38.82686	DMASS=	0.675335E-10
FL=	.000001696	VL=	502.419527	TS=	457.677135	D=	48.92955	DMASS=	0.135156E-09
FL=	.000000172	VL=	494.578244	TS=	458.892349	D=	58.98666	DMASS=	0.236801E-09
FL=	.000000017	VL=	480.442148	TS=	460.765920	D=	79.03480	DMASS=	0.569610E-09
FL=	.000000002	VL=	467.888907	TS=	462.150181	D=	99.04257	DMASS=	0.112095E-08
X=	26.504321	YDUCT=	4.474166	MG=	.533468	PO=	2075.5801	TO=	474.853069
DX=	.007000000	A(X)=	62.8889	A(X)/A0=	.08241	REL HUM. %=		82.184253	
CV=	.000572131	VG=	556.791448	TG=	448.842442	P=	1708.44	FLtot=	.000109402
FL=	.000006246	VL=	554.914564	TS=	448.824951	D=	6.11609	DMASS=	0.263963E-12
FL=	.000037618	VL=	549.971273	TS=	450.077484	D=	12.59786	DMASS=	0.230681E-11
FL=	.000035793	VL=	544.747911	TS=	451.301480	D=	18.14885	DMASS=	0.689716E-11
FL=	.000023708	VL=	534.619594	TS=	453.509958	D=	28.62182	DMASS=	0.270529E-10
FL=	.000004151	VL=	525.301257	TS=	455.369435	D=	38.82441	DMASS=	0.675207E-10
FL=	.000001696	VL=	516.752194	TS=	456.914818	D=	48.92687	DMASS=	0.135134E-09
FL=	.000000172	VL=	508.846682	TS=	458.199398	D=	58.98377	DMASS=	0.236766E-09
FL=	.000000017	VL=	494.564148	TS=	460.182976	D=	79.03159	DMASS=	0.569541E-09
FL=	.000000002	VL=	481.854610	TS=	461.648088	D=	99.03911	DMASS=	0.112084E-08
X=	27.001321	YDUCT=	4.436968	MG=	.546950	PO=	2075.5766	TO=	474.855602
DX=	.007000000	A(X)=	61.8475	A(X)/A0=	.08104	REL HUM. %=		86.602750	
CV=	.000572166	VG=	570.074388	TG=	447.586719	P=	1691.98	FLtot=	.000109367
FL=	.000006240	VL=	568.239364	TS=	447.728893	D=	6.11422	DMASS=	0.263722E-12

FL=	.000037604	VL=	563.390503	TS=	449.010571	D=	12.59632	DMASS=	0.230597E-11
FL=	.000035783	VL=	558.243454	TS=	450.279555	D=	18.14724	DMASS=	0.689532E-11
FL=	.000023703	VL=	548.195732	TS=	452.585983	D=	28.61993	DMASS=	0.270476E-10
FL=	.000004151	VL=	538.897920	TS=	454.535542	D=	38.82224	DMASS=	0.675094E-10
FL=	.000001696	VL=	530.337239	TS=	456.159422	D=	48.92445	DMASS=	0.135114E-09
FL=	.000000172	VL=	522.401193	TS=	457.511560	D=	58.98114	DMASS=	0.236735E-09
FL=	.000000017	VL=	508.025819	TS=	459.602939	D=	79.02862	DMASS=	0.569476E-09
FL=	.000000002	VL=	495.201273	TS=	461.147772	D=	99.03588	DMASS=	0.112073E-08

X=	27.505321	YDUCT=	4.402649	MG=	.560105	PO=	2075.5731	TO=	474.858263
DX=	.007000000	A(X)=	60.8945	A(X)/AO=	.07979	REL HUM. %=			91.262593

CV=	.000572194	VG=	582.981110	TG=	446.338130	P=	1675.73	Fltot=	.000109339
FL=	.000006236	VL=	581.177574	TS=	446.636168	D=	6.11288	DMASS=	0.263549E-12
FL=	.000037593	VL=	576.399914	TS=	447.943788	D=	12.59511	DMASS=	0.230531E-11
FL=	.000035775	VL=	571.319862	TS=	449.252991	D=	18.14590	DMASS=	0.689379E-11
FL=	.000023699	VL=	561.366018	TS=	451.652344	D=	28.61826	DMASS=	0.270428E-10
FL=	.000004150	VL=	552.113851	TS=	453.690119	D=	38.82027	DMASS=	0.674992E-10
FL=	.000001695	VL=	543.567117	TS=	455.391867	D=	48.92222	DMASS=	0.135096E-09
FL=	.000000172	VL=	535.624200	TS=	456.811481	D=	58.97868	DMASS=	0.236705E-09
FL=	.000000017	VL=	521.196562	TS=	459.011186	D=	79.02580	DMASS=	0.569415E-09
FL=	.000000002	VL=	508.289822	TS=	460.636604	D=	99.03278	DMASS=	0.112062E-08

X=	28.002321	YDUCT=	4.371915	MG=	.572538	PO=	2075.5695	TO=	474.860958
DX=	.007000000	A(X)=	60.0473	A(X)/AO=	.07868	REL HUM. %=			96.011516

CV=	.000572215	VG=	595.129444	TG=	445.137298	P=	1660.20	Fltot=	.000109318
FL=	.000006233	VL=	593.366224	TS=	445.577887	D=	6.11206	DMASS=	0.263442E-12
FL=	.000037585	VL=	588.673128	TS=	446.907613	D=	12.59423	DMASS=	0.230482E-11
FL=	.000035769	VL=	583.661353	TS=	448.251915	D=	18.14484	DMASS=	0.689258E-11
FL=	.000023695	VL=	573.806430	TS=	450.736791	D=	28.61684	DMASS=	0.270388E-10
FL=	.000004149	VL=	564.613154	TS=	452.858366	D=	38.81854	DMASS=	0.674901E-10
FL=	.000001695	VL=	556.098862	TS=	454.635066	D=	48.92022	DMASS=	0.135079E-09
FL=	.000000172	VL=	548.164286	TS=	456.120087	D=	58.97645	DMASS=	0.236678E-09
FL=	.000000017	VL=	533.717398	TS=	458.425435	D=	79.02320	DMASS=	0.569359E-09
FL=	.000000002	VL=	520.758031	TS=	460.129895	D=	99.02990	DMASS=	0.112052E-08

X=	28.506321	YDUCT=	4.343645	MG=	.584580	PO=	2075.5658	TO=	474.863738
DX=	.007000000	A(X)=	59.2732	A(X)/AO=	.07767	REL HUM. %=			100.958962

CV=	.000572230	VG=	606.849747	TG=	443.955236	P=	1645.01	Fltot=	.000109303
FL=	.000006232	VL=	605.129592	TS=	444.529184	D=	6.11167	DMASS=	0.263392E-12
FL=	.000037579	VL=	600.538437	TS=	445.876084	D=	12.59361	DMASS=	0.230448E-11
FL=	.000035764	VL=	595.609033	TS=	447.251251	D=	18.14400	DMASS=	0.689162E-11
FL=	.000023692	VL=	585.870973	TS=	449.816234	D=	28.61562	DMASS=	0.270353E-10
FL=	.000004149	VL=	576.752456	TS=	452.019154	D=	38.81698	DMASS=	0.674820E-10
FL=	.000001695	VL=	568.282470	TS=	453.869709	D=	48.91838	DMASS=	0.135064E-09
FL=	.000000172	VL=	560.375759	TS=	455.419690	D=	58.97437	DMASS=	0.236653E-09
FL=	.000000017	VL=	545.938513	TS=	457.830656	D=	79.02073	DMASS=	0.569306E-09
FL=	.000000002	VL=	532.951974	TS=	459.614614	D=	99.02714	DMASS=	0.112043E-08

X=	29.003321	YDUCT=	4.317875	MG=	.596120	PO=	2075.5621	TO=	474.866560
DX=	.007000000	A(X)=	58.5720	A(X)/AO=	.07675	REL HUM. %=			106.048075

CV=	.000572240	VG=	618.037327	TG=	442.805327	P=	1630.34	FLtot=	.000109293
FL=	.000006232	VL=	616.326093	TS=	443.511788	D=	6.11169	DMASS=	0.263394E-12
FL=	.000037576	VL=	611.784429	TS=	444.875702	D=	12.59325	DMASS=	0.230429E-11
FL=	.000035760	VL=	606.917009	TS=	446.278216	D=	18.14339	DMASS=	0.689093E-11
FL=	.000023690	VL=	597.285049	TS=	448.916689	D=	28.61460	DMASS=	0.270325E-10
FL=	.000004149	VL=	588.242881	TS=	451.196478	D=	38.81563	DMASS=	0.674749E-10
FL=	.000001695	VL=	579.825593	TS=	453.117804	D=	48.91673	DMASS=	0.135050E-09
FL=	.000000172	VL=	571.953403	TS=	454.730505	D=	58.97248	DMASS=	0.236630E-09
FL=	.000000017	VL=	557.545646	TS=	457.244095	D=	79.01846	DMASS=	0.569257E-09
FL=	.000000002	VL=	544.552197	TS=	459.105738	D=	99.02456	DMASS=	0.112034E-08
X=	29.500321	YDUCT=	4.293277	MG=	.607690	PO=	2075.5582	TO=	474.869539
DX=	.007000000	A(X)=	57.9065	A(X)/A0=	.07588	REL HUM. %	111.521491		
CV=	.000572245	VG=	629.211406	TG=	441.635759	P=	1615.51	FLtot=	.000109288
FL=	.000006233	VL=	627.465450	TS=	442.486930	D=	6.11208	DMASS=	0.263444E-12
FL=	.000037575	VL=	622.867494	TS=	443.879251	D=	12.59313	DMASS=	0.230422E-11
FL=	.000035758	VL=	617.993595	TS=	445.310386	D=	18.14298	DMASS=	0.689046E-11
FL=	.000023688	VL=	608.400210	TS=	448.020541	D=	28.61375	DMASS=	0.270301E-10
FL=	.000004148	VL=	599.404810	TS=	450.375452	D=	38.81443	DMASS=	0.674687E-10
FL=	.000001695	VL=	591.026117	TS=	452.366379	D=	48.91524	DMASS=	0.135038E-09
FL=	.000000172	VL=	583.182120	TS=	454.041025	D=	58.97074	DMASS=	0.236610E-09
FL=	.000000017	VL=	568.802566	TS=	456.656373	D=	79.01632	DMASS=	0.569211E-09
FL=	.000000002	VL=	555.807795	TS=	458.595347	D=	99.02212	DMASS=	0.112026E-08
X=	30.004321	YDUCT=	4.269846	MG=	.619272	PO=	2075.5541	TO=	474.872680
DX=	.007000000	A(X)=	57.2762	A(X)/A0=	.07505	REL HUM. %	117.402896		
CV=	.000572246	VG=	640.352138	TG=	440.448742	P=	1600.56	FLtot=	.000109287
FL=	.000006236	VL=	638.604045	TS=	441.436963	D=	6.11282	DMASS=	0.263540E-12
FL=	.000037576	VL=	633.983458	TS=	442.865491	D=	12.59321	DMASS=	0.230426E-11
FL=	.000035756	VL=	629.084191	TS=	444.328375	D=	18.14274	DMASS=	0.689019E-11
FL=	.000023686	VL=	619.479423	TS=	447.111310	D=	28.61305	DMASS=	0.270281E-10
FL=	.000004148	VL=	610.497244	TS=	449.541649	D=	38.81337	DMASS=	0.674631E-10
FL=	.000001695	VL=	602.136128	TS=	451.602606	D=	48.91388	DMASS=	0.135026E-09
FL=	.000000172	VL=	594.307100	TS=	453.339719	D=	58.96912	DMASS=	0.236590E-09
FL=	.000000017	VL=	579.942498	TS=	456.057935	D=	79.01429	DMASS=	0.569167E-09
FL=	.000000002	VL=	566.942406	TS=	458.075298	D=	99.01978	DMASS=	0.112018E-08
X=	30.501321	YDUCT=	4.248294	MG=	.630462	PO=	2075.5500	TO=	474.875871
DX=	.007000000	A(X)=	56.6995	A(X)/A0=	.07430	REL HUM. %	123.499791		
CV=	.000572242	VG=	651.073370	TG=	439.286677	P=	1586.01	FLtot=	.000109291
FL=	.000006239	VL=	649.334689	TS=	440.400745	D=	6.11387	DMASS=	0.263676E-12
FL=	.000037578	VL=	644.725843	TS=	441.864720	D=	12.59349	DMASS=	0.230442E-11
FL=	.000035756	VL=	639.819815	TS=	443.360281	D=	18.14268	DMASS=	0.689012E-11
FL=	.000023685	VL=	630.200846	TS=	446.214554	D=	28.61251	DMASS=	0.270265E-10
FL=	.000004148	VL=	621.218058	TS=	448.718365	D=	38.81246	DMASS=	0.674584E-10
FL=	.000001694	VL=	612.862384	TS=	450.847762	D=	48.91267	DMASS=	0.135016E-09
FL=	.000000172	VL=	605.039315	TS=	452.646100	D=	58.96765	DMASS=	0.236572E-09
FL=	.000000017	VL=	590.679325	TS=	455.465426	D=	79.01241	DMASS=	0.569126E-09
FL=	.000000002	VL=	577.670307	TS=	457.560062	D=	99.01758	DMASS=	0.112011E-08

X=	31.005321	YDUCT=	4.227821	MG=	.641624	PO=	2075.5456	TO=	474.879208
DX=	.007000000	A(X)=	56.1543	A(X)/AO=	.07358	REL HUM. %	130.020404		
CV=	.000572235	VG=	661.724706	TG=	438.113004	P=	1571.42	FLtot=	.000109299
FL=	.000006243	VL=	659.985981	TS=	439.351409	D=	6.11524	DMASS=	0.263853E-12
FL=	.000037583	VL=	655.385438	TS=	440.850182	D=	12.59396	DMASS=	0.230467E-11
FL=	.000035757	VL=	650.481290	TS=	442.379580	D=	18.14277	DMASS=	0.689022E-11
FL=	.000023684	VL=	640.854824	TS=	445.305570	D=	28.61210	DMASS=	0.270254E-10
FL=	.000004147	VL=	631.867891	TS=	447.882863	D=	38.81167	DMASS=	0.674543E-10
FL=	.000001694	VL=	623.512197	TS=	450.080953	D=	48.91157	DMASS=	0.135007E-09
FL=	.000000172	VL=	615.690225	TS=	451.940936	D=	58.96629	DMASS=	0.236556E-09
FL=	.000000017	VL=	601.328504	TS=	454.862390	D=	79.01063	DMASS=	0.569087E-09
FL=	.000000002	VL=	588.308004	TS=	457.035317	D=	99.01547	DMASS=	0.112004E-08
X=	31.502321	YDUCT=	4.208571	MG=	.652643	PO=	2075.5411	TO=	474.882650
DX=	.007000000	A(X)=	55.6441	A(X)/AO=	.07291	REL HUM. %	136.924224		
CV=	.000572224	VG=	672.198726	TG=	436.940215	P=	1556.94	FLtot=	.000109310
FL=	.000006248	VL=	670.444588	TS=	438.306391	D=	6.11686	DMASS=	0.264064E-12
FL=	.000037588	VL=	665.796525	TS=	439.844795	D=	12.59459	DMASS=	0.230502E-11
FL=	.000035758	VL=	660.865891	TS=	441.409751	D=	18.14301	DMASS=	0.689049E-11
FL=	.000023683	VL=	651.208704	TS=	444.407399	D=	28.61183	DMASS=	0.270246E-10
FL=	.000004147	VL=	642.204088	TS=	447.056858	D=	38.81102	DMASS=	0.674509E-10
FL=	.000001694	VL=	633.837988	TS=	449.322369	D=	48.91061	DMASS=	0.134999E-09
FL=	.000000172	VL=	626.009021	TS=	451.242943	D=	58.96506	DMASS=	0.236541E-09
FL=	.000000017	VL=	611.634749	TS=	454.264982	D=	79.00898	DMASS=	0.569052E-09
FL=	.000000002	VL=	598.597070	TS=	456.515201	D=	99.01349	DMASS=	0.111997E-08
X=	32.006321	YDUCT=	4.190821	MG=	.663305	PO=	2075.5365	TO=	474.886139
DX=	.007000000	A(X)=	55.1757	A(X)/AO=	.07230	REL HUM. %	144.081356		
CV=	.000572209	VG=	682.293765	TG=	435.792367	P=	1542.86	FLtot=	.000109324
FL=	.000006254	VL=	680.617356	TS=	437.256172	D=	6.11877	DMASS=	0.264311E-12
FL=	.000037595	VL=	676.062864	TS=	438.827004	D=	12.59540	DMASS=	0.230546E-11
FL=	.000035760	VL=	671.155089	TS=	440.427279	D=	18.14338	DMASS=	0.689092E-11
FL=	.000023683	VL=	661.497365	TS=	443.496781	D=	28.61168	DMASS=	0.270242E-10
FL=	.000004147	VL=	652.482517	TS=	446.218508	D=	38.81048	DMASS=	0.674481E-10
FL=	.000001694	VL=	644.107180	TS=	448.551732	D=	48.90974	DMASS=	0.134992E-09
FL=	.000000172	VL=	636.270395	TS=	450.533334	D=	58.96393	DMASS=	0.236528E-09
FL=	.000000017	VL=	621.880996	TS=	453.656993	D=	79.00741	DMASS=	0.569018E-09
FL=	.000000002	VL=	608.824469	TS=	455.985534	D=	99.01159	DMASS=	0.111990E-08
X=	32.503321	YDUCT=	4.175681	MG=	.672823	PO=	2075.5321	TO=	474.889406
DX=	.007000000	A(X)=	54.7778	A(X)/AO=	.07178	REL HUM. %	150.896891		
CV=	.000572192	VG=	691.271653	TG=	434.757133	P=	1530.24	FLtot=	.000109342
FL=	.000006260	VL=	689.751387	TS=	436.275209	D=	6.12088	DMASS=	0.264584E-12
FL=	.000037604	VL=	685.473163	TS=	437.849954	D=	12.59633	DMASS=	0.230597E-11
FL=	.000035763	VL=	680.713102	TS=	439.476698	D=	18.14388	DMASS=	0.689149E-11
FL=	.000023682	VL=	671.182255	TS=	442.609915	D=	28.61164	DMASS=	0.270241E-10
FL=	.000004147	VL=	662.218051	TS=	445.399106	D=	38.81005	DMASS=	0.674458E-10
FL=	.000001694	VL=	653.868448	TS=	447.796736	D=	48.90900	DMASS=	0.134986E-09

FL= .000000172 VL= 646.046505 TS= 449.836958 D= 58.96292 DMASS= 0.236515E-09
FL= .000000017 VL= 631.670135 TS= 453.059011 D= 79.00597 DMASS= 0.568987E-09
FL= .000000002 VL= 618.612563 TS= 455.463879 D= 99.00982 DMASS= 0.111984E-08

X= 33.000321 YDUCT= 4.163013 MG= .681117 PO= 2075.5279 TO= 474.892388
DX= .007000000 A(X)= 54.4459 A(X)/AO= .07134 REL HUM. %= 157.187553

CV= .000572172 VG= 699.069554 TG= 433.846968 P= 1519.20 FLtot= .000109362
FL= .000006267 VL= 697.748833 TS= 435.384559 D= 6.12317 DMASS= 0.264881E-12
FL= .000037613 VL= 693.870302 TS= 436.926322 D= 12.59738 DMASS= 0.230655E-11
FL= .000035767 VL= 689.382301 TS= 438.564549 D= 18.14448 DMASS= 0.689217E-11
FL= .000023683 VL= 680.145158 TS= 441.747903 D= 28.61171 DMASS= 0.270243E-10
FL= .000004147 VL= 671.328224 TS= 444.597494 D= 38.80974 DMASS= 0.674442E-10
FL= .00001694 VL= 663.066592 TS= 447.055113 D= 48.90837 DMASS= 0.134981E-09
FL= .00000172 VL= 655.303160 TS= 449.150976 D= 58.96202 DMASS= 0.236505E-09
FL= .00000017 VL= 640.997971 TS= 452.467772 D= 79.00464 DMASS= 0.568958E-09
FL= .000000002 VL= 627.977419 TS= 454.946926 D= 99.00815 DMASS= 0.111979E-08

X= 33.504321 YDUCT= 4.153004 MG= .687901 PO= 2075.5242 TO= 474.894957
DX= .007000000 A(X)= 54.1844 A(X)/AO= .07100 REL HUM. %= 162.590335

CV= .000572149 VG= 705.429941 TG= 433.097055 P= 1510.15 FLtot= .000109384
FL= .000006275 VL= 704.379989 TS= 434.609558 D= 6.12564 DMASS= 0.265202E-12
FL= .000037624 VL= 701.067875 TS= 436.072761 D= 12.59855 DMASS= 0.230719E-11
FL= .000035771 VL= 696.991854 TS= 437.701065 D= 18.14519 DMASS= 0.689298E-11
FL= .000023683 VL= 688.245747 TS= 440.914812 D= 28.61187 DMASS= 0.270247E-10
FL= .000004147 VL= 679.700571 TS= 443.814949 D= 38.80951 DMASS= 0.674430E-10
FL= .00001694 VL= 671.612120 TS= 446.326649 D= 48.90784 DMASS= 0.134976E-09
FL= .00000172 VL= 663.969670 TS= 448.474306 D= 58.96122 DMASS= 0.236495E-09
FL= .00000017 VL= 649.822369 TS= 451.881348 D= 79.00340 DMASS= 0.568931E-09
FL= .000000002 VL= 636.897424 TS= 454.432434 D= 99.00657 DMASS= 0.111973E-08

X= 34.001321 YDUCT= 4.145995 MG= .692781 PO= 2075.5212 TO= 474.896927
DX= .007000000 A(X)= 54.0017 A(X)/AO= .07076 REL HUM. %= 166.625047

CV= .000572125 VG= 709.994735 TG= 432.554726 P= 1503.63 FLtot= .000109408
FL= .000006283 VL= 709.254261 TS= 434.002968 D= 6.12818 DMASS= 0.265532E-12
FL= .000037635 VL= 706.633266 TS= 435.340610 D= 12.59977 DMASS= 0.230787E-11
FL= .000035775 VL= 703.097914 TS= 436.932803 D= 18.14595 DMASS= 0.689385E-11
FL= .000023684 VL= 695.037561 TS= 440.150257 D= 28.61211 DMASS= 0.270254E-10
FL= .000004147 VL= 686.894858 TS= 443.086242 D= 38.80939 DMASS= 0.674424E-10
FL= .00001694 VL= 679.073259 TS= 445.642333 D= 48.90741 DMASS= 0.134973E-09
FL= .00000172 VL= 671.622911 TS= 447.834860 D= 58.96053 DMASS= 0.236487E-09
FL= .00000017 VL= 657.735914 TS= 451.322935 D= 79.00229 DMASS= 0.568907E-09
FL= .000000002 VL= 644.978283 TS= 453.940185 D= 99.00513 DMASS= 0.111968E-08

X= 34.505321 YDUCT= 4.142291 MG= .695406 PO= 2075.5191 TO= 474.898149
DX= .007000000 A(X)= 53.9053 A(X)/AO= .07063 REL HUM. %= 168.844664

CV= .000572100 VG= 712.446682 TG= 432.262115 P= 1500.12 FLtot= .000109433
FL= .000006291 VL= 712.092135 TS= 433.589626 D= 6.13081 DMASS= 0.265874E-12
FL= .000037646 VL= 710.400697 TS= 434.741555 D= 12.60105 DMASS= 0.230857E-11
FL= .000035780 VL= 707.595902 TS= 436.264587 D= 18.14678 DMASS= 0.689479E-11

FL=	.000023684	VL=	700.473695	TS=	439.452174	D=	28.61243	DMASS=	0.270263E-10
FL=	.000004147	VL=	692.894514	TS=	442.406292	D=	38.80934	DMASS=	0.674421E-10
FL=	.000001694	VL=	685.454715	TS=	444.995656	D=	48.90706	DMASS=	0.134970E-09
FL=	.000000172	VL=	678.284421	TS=	447.225460	D=	58.95993	DMASS=	0.236479E-09
FL=	.000000017	VL=	664.786181	TS=	450.785024	D=	79.00127	DMASS=	0.568885E-09
FL=	.000000002	VL=	652.287180	TS=	453.462865	D=	99.00378	DMASS=	0.111964E-08
X=	35.002321	YDUCT=	4.140999	MG=	.696329	PO=	2075.5179	TO=	474.898767
DX=	.007000000	A(X)=	53.8716	A(X)/A0=	.07059	REL HUM. %=	169.627466		
CV=	.000572075	VG=	713.307912	TG=	432.159283	P=	1498.88	Fltot=	.000109458
FL=	.000006299	VL=	713.221453	TS=	433.374607	D=	6.13340	DMASS=	0.266211E-12
FL=	.000037657	VL=	712.365575	TS=	434.304917	D=	12.60232	DMASS=	0.230926E-11
FL=	.000035785	VL=	710.366129	TS=	435.729353	D=	18.14761	DMASS=	0.689574E-11
FL=	.000023685	VL=	704.350944	TS=	438.852854	D=	28.61279	DMASS=	0.270273E-10
FL=	.000004147	VL=	697.458916	TS=	441.805023	D=	38.80936	DMASS=	0.674423E-10
FL=	.000001694	VL=	690.494370	TS=	444.414086	D=	48.90681	DMASS=	0.134968E-09
FL=	.000000172	VL=	683.678649	TS=	446.671311	D=	58.95944	DMASS=	0.236474E-09
FL=	.000000017	VL=	670.682994	TS=	450.289048	D=	79.00038	DMASS=	0.568866E-09
FL=	.000000002	VL=	658.527330	TS=	453.019006	D=	99.00256	DMASS=	0.111960E-08
X=	35.506321	YDUCT=	4.141512	MG=	.695960	PO=	2075.5172	TO=	474.898919
DX=	.007000000	A(X)=	53.8850	A(X)/A0=	.07061	REL HUM. %=	169.300693		
CV=	.000572050	VG=	712.964492	TG=	432.200702	P=	1499.37	Fltot=	.000109483
FL=	.000006307	VL=	713.081749	TS=	433.312997	D=	6.13600	DMASS=	0.266550E-12
FL=	.000037669	VL=	712.952415	TS=	434.009767	D=	12.60356	DMASS=	0.230995E-11
FL=	.000035790	VL=	711.758638	TS=	435.310196	D=	18.14845	DMASS=	0.689670E-11
FL=	.000023686	VL=	706.945811	TS=	438.337685	D=	28.61318	DMASS=	0.270284E-10
FL=	.000004147	VL=	700.829729	TS=	441.268716	D=	38.80944	DMASS=	0.674427E-10
FL=	.000001694	VL=	694.413515	TS=	443.884619	D=	48.90662	DMASS=	0.134966E-09
FL=	.000000172	VL=	688.013968	TS=	446.160096	D=	58.95902	DMASS=	0.236469E-09
FL=	.000000017	VL=	675.620436	TS=	449.823960	D=	78.99957	DMASS=	0.568849E-09
FL=	.000000002	VL=	663.886142	TS=	452.598647	D=	99.00144	DMASS=	0.111956E-08
X=	36.003321	YDUCT=	4.143008	MG=	.694893	PO=	2075.5171	TO=	474.898801
DX=	.007000000	A(X)=	53.9239	A(X)/A0=	.07066	REL HUM. %=	168.377039		
CV=	.000572025	VG=	711.968545	TG=	432.320146	P=	1500.80	Fltot=	.000109508
FL=	.000006315	VL=	712.179722	TS=	433.360950	D=	6.13861	DMASS=	0.266890E-12
FL=	.000037680	VL=	712.552073	TS=	433.828129	D=	12.60480	DMASS=	0.231063E-11
FL=	.000035795	VL=	712.080574	TS=	435.011677	D=	18.14923	DMASS=	0.689759E-11
FL=	.000023687	VL=	708.437747	TS=	437.916704	D=	28.61358	DMASS=	0.270296E-10
FL=	.000004147	VL=	703.111101	TS=	440.810139	D=	38.80956	DMASS=	0.674433E-10
FL=	.000001694	VL=	697.264917	TS=	443.420926	D=	48.90650	DMASS=	0.134965E-09
FL=	.000000172	VL=	691.305403	TS=	445.705580	D=	58.95868	DMASS=	0.236464E-09
FL=	.000000017	VL=	679.561484	TS=	449.402813	D=	78.99887	DMASS=	0.568834E-09
FL=	.000000002	VL=	668.292353	TS=	452.213821	D=	99.00044	DMASS=	0.111953E-08
X=	36.500321	YDUCT=	4.144623	MG=	.693752	PO=	2075.5145	TO=	474.900330
DX=	.007000000	A(X)=	53.9660	A(X)/A0=	.07071	REL HUM. %=	167.432146		
CV=	.000572169	VG=	710.903867	TG=	432.449312	P=	1502.33	Fltot=	.000109364

3/13/98 5:15 PM Hard Disk 2150:MPW:AEDC ADVERSE WEATHER 3/98:DEVELOPMENTS OF AEDC MFF CODE:AEDCIDMP ...:AEDCIDMP.OUT

FL=	.000006323	VL=	711.105286	TS=	433.462180	D=	6.14122	DMASS=	0.267231E-12
FL=	.000037691	VL=	711.663720	TS=	433.727839	D=	12.60611	DMASS=	0.231135E-11
FLM=	.000035668	VLM=	711.720251	TSM=	492.000000	DM=	18.56372	DMASS=	0.689246E-11
FLM=	.000023651	VLM=	709.247766	TSM=	492.000000	DM=	29.18043	DMASS=	0.270209E-10
FL=	.000004147	VL=	704.618111	TS=	440.413440	D=	38.80971	DMASS=	0.674441E-10
FL=	.000001694	VL=	699.335050	TS=	443.009400	D=	48.90643	DMASS=	0.134965E-09
FL=	.000000172	VL=	693.818235	TS=	445.295824	D=	58.95841	DMASS=	0.236461E-09
FL=	.000000017	VL=	682.741590	TS=	449.015989	D=	78.99825	DMASS=	0.568820E-09
FL=	.000000002	VL=	671.961265	TS=	451.856450	D=	98.99953	DMASS=	0.111949E-08

X=	37.004321	YDOCT=	4.146003	MG=	.692783	PO=	2075.5117	TO=	474.902081
DX=	.007000000	A(X)=	54.0019	A(X)/AO=	.07076	REL HUM. %=	166.643317		

CV=	.000572329	VG=	710.000484	TG=	432.559215	P=	1503.62	FLtot=	.000109204
FL=	.000006331	VL=	710.147072	TS=	433.572388	D=	6.14385	DMASS=	0.267574E-12
FL=	.000037704	VL=	710.688986	TS=	433.689324	D=	12.60745	DMASS=	0.231209E-11
FLM=	.000035526	VLM=	711.014084	TSM=	492.000000	DM=	18.61089	DMASS=	0.688670E-11
FLM=	.000023612	VLM=	709.550546	TSM=	492.000000	DM=	29.21153	DMASS=	0.270115E-10
FL=	.000004147	VL=	705.609773	TS=	440.063329	D=	38.80988	DMASS=	0.674450E-10
FL=	.000001694	VL=	700.864203	TS=	442.636804	D=	48.90639	DMASS=	0.134964E-09
FL=	.000000172	VL=	695.778449	TS=	444.919172	D=	58.95818	DMASS=	0.236458E-09
FL=	.000000017	VL=	685.365647	TS=	448.654061	D=	78.99769	DMASS=	0.568808E-09
FL=	.000000002	VL=	675.082785	TS=	451.518608	D=	98.99869	DMASS=	0.111947E-08

X=	37.501321	YDOCT=	4.146187	MG=	.692660	PO=	2075.5087	TO=	474.904059
DX=	.007000000	A(X)=	54.0067	A(X)/AO=	.07077	REL HUM. %=	166.568518		

CV=	.000572486	VG=	709.886670	TG=	432.574819	P=	1503.78	FLtot=	.000109047
FL=	.000006339	VL=	709.888497	TS=	433.636318	D=	6.14637	DMASS=	0.267904E-12
FL=	.000037715	VL=	710.123388	TS=	433.679486	D=	12.60875	DMASS=	0.231280E-11
FLM=	.000035389	VLM=	710.443707	TSM=	492.000000	DM=	18.65670	DMASS=	0.688106E-11
FLM=	.000023576	VLM=	709.639990	TSM=	492.000000	DM=	29.24004	DMASS=	0.270029E-10
FLM=	.000004143	VLM=	706.352437	TSM=	492.000000	DM=	39.51378	DMASS=	0.674336E-10
FL=	.000001694	VL=	702.032771	TS=	442.301697	D=	48.90638	DMASS=	0.134964E-09
FL=	.000000172	VL=	697.338793	TS=	444.576628	D=	58.95800	DMASS=	0.236456E-09
FL=	.000000017	VL=	687.543584	TS=	448.320475	D=	78.99719	DMASS=	0.568797E-09
FL=	.000000002	VL=	677.734367	TS=	451.204719	D=	98.99792	DMASS=	0.111944E-08

X=	38.005321	YDOCT=	4.146000	MG=	.692797	PO=	2075.5059	TO=	474.905894
DX=	.007000000	A(X)=	54.0018	A(X)/AO=	.07076	REL HUM. %=	166.781018		

CV=	.000572871	VG=	710.016227	TG=	432.561175	P=	1503.60	FLtot=	.000108662
FL=	.000006347	VL=	709.987269	TS=	433.651218	D=	6.14891	DMASS=	0.268235E-12
FL=	.000037727	VL=	710.003625	TS=	433.673068	D=	12.61002	DMASS=	0.231350E-11
FLI=	.000035025	VLI=	710.194488	TSL=	475.261419	DI=	18.60569	DMASS=	0.681442E-11
FLM=	.000023540	VLM=	709.716611	TSM=	492.000000	DM=	29.26873	DMASS=	0.269942E-10
FLM=	.000004139	VLM=	706.978261	TSM=	492.000000	DM=	39.54103	DMASS=	0.674185E-10
FL=	.000001694	VL=	703.033115	TS=	441.984310	D=	48.90640	DMASS=	0.134965E-09
FL=	.000000172	VL=	698.696002	TS=	444.250202	D=	58.95785	DMASS=	0.236454E-09
FL=	.000000017	VL=	689.477453	TS=	447.999920	D=	78.99673	DMASS=	0.568787E-09
FL=	.000000002	VL=	680.120811	TS=	450.901454	D=	98.99720	DMASS=	0.111942E-08

X=	38.502321	YDOCT=	4.146000	MG=	.692801	PO=	2075.5038	TO=	474.907283
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DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	166.804816
CV=	.000572981	VG=	710.020877	TG=	432.562016	P=	1503.59
FL=	.000006355	VL=	710.019874	TS=	433.652079	D=	6.15139
FL=	.000037737	VL=	710.014585	TS=	433.667365	D=	12.61123
FL=	.000034936	VLI=	710.108359	TSI=	466.635660	DI=	18.58992
FL=	.000023504	VLM=	709.791484	TSM=	492.000000	DM=	29.29697
FL=	.00004135	VLM=	707.490671	TSM=	492.000000	DM=	39.56726
FL=	.000001694	VL=	703.879425	TS=	441.690457	D=	48.90644
FL=	.000000172	VL=	699.858889	TS=	443.946339	D=	58.95772
FL=	.000000017	VL=	691.163458	TS=	447.699286	D=	78.99632
FL=	.000000002	VL=	682.225918	TS=	450.615642	D=	98.99654
X=	39.006321	YDUCT=	4.146000	MG=	.692804	PO=	2075.5020
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	166.812549
CV=	.000573033	VG=	710.024898	TG=	432.562773	P=	1503.58
FL=	.000006362	VL=	710.024158	TS=	433.653164	D=	6.15391
FL=	.000037749	VL=	710.020825	TS=	433.663494	D=	12.61247
FL=	.000034906	VLI=	710.066651	TSI=	460.929042	DI=	18.58459
FL=	.000023468	VLM=	709.849308	TSM=	492.000000	DM=	29.32525
FL=	.000004131	VLM=	707.914045	TSM=	492.000000	DM=	39.59319
FL=	.000001693	VLM=	704.658976	TSM=	492.000000	DM=	49.74205
FL=	.000000172	VL=	700.882051	TS=	443.655263	D=	58.95762
FL=	.000000017	VL=	692.676548	TS=	447.409067	D=	78.99594
FL=	.000000002	VL=	684.138603	TS=	450.338372	D=	98.99591
X=	39.503321	YDUCT=	4.146000	MG=	.692813	PO=	2075.4970
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	166.863990
CV=	.000573276	VG=	710.035790	TG=	432.564754	P=	1503.57
FL=	.000006370	VL=	710.033289	TS=	433.654795	D=	6.15639
FL=	.000037547	VLM=	710.028366	TSM=	492.000000	DM=	12.92658
FL=	.000034896	VLI=	710.049115	TSI=	456.725282	DI=	18.58287
FL=	.000023433	VLM=	709.893695	TSM=	492.000000	DM=	29.35287
FL=	.000004127	VLM=	708.256994	TSM=	492.000000	DM=	39.61819
FL=	.000001692	VLM=	705.330263	TSM=	492.000000	DM=	49.76587
FL=	.000000172	VL=	701.763142	TS=	443.383436	D=	58.95755
FL=	.000000017	VL=	694.004302	TS=	447.136039	D=	78.99559
FL=	.000000002	VL=	685.836604	TS=	450.076304	D=	98.99533
X=	40.000321	YDUCT=	4.146000	MG=	.692824	PO=	2075.4912
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	166.987665
CV=	.000573778	VG=	710.048966	TG=	432.567007	P=	1503.55
FL=	.000006378	VL=	710.046373	TS=	433.657924	D=	6.15887
FL=	.000037078	VLI=	710.040018	TSI=	481.096710	DI=	12.94241
FL=	.000034896	VLI=	710.046205	TSI=	453.412512	DI=	18.58273
FL=	.000023399	VLM=	709.930259	TSM=	492.000000	DM=	29.38027
FL=	.000004123	VLM=	708.541968	TSM=	492.000000	DM=	39.64268
FL=	.000001690	VLM=	705.905220	TSM=	492.000000	DM=	49.78911
FL=	.000000172	VL=	702.538347	TS=	443.125333	D=	58.95749
FL=	.000000017</						

3/13/98 5:15 PM Hard Disk 2150:MEW:AEDC ADVERSE WEATHER 3/98:DEVELOPMENTS OF AEDC MTF CODE:AEDCLIMP ...:AEDCLIMP.OUT

FL=	.000000002	VL=	687.373442	TS=	449.824616	D=	98.99478	DMASS=	0.111933E-08
X=	40.504321	YDUCT=	4.146000	MG=	.692832	PO=	2075.4870	TO=	474.918309
DX=	.007000000	A(X)=	54.0018	A(X)/AO=	.07076	REL HUM. %=	167.042370		
CV=	.000574021	VG=	710.058161	TG=	432.568653	P=	1503.54	FLtot=	.000107510
FL=	.000006386	VL=	710.056619	TS=	433.661644	D=	6.16140	DMASS=	0.269873E-12
FLI=	.000036862	VLI=	710.051209	TSI=	463.030942	DI=	12.91728	DMASS=	0.228037E-11
FLI=	.000034899	VLI=	710.050128	TSI=	450.652106	DI=	18.58343	DMASS=	0.678999E-11
FLM=	.000023364	VLM=	709.960999	TSM=	492.000000	DM=	29.40787	DMASS=	0.269518E-10
FLM=	.000004119	VLM=	708.783055	TSM=	492.000000	DM=	39.66706	DMASS=	0.673485E-10
FLM=	.000001689	VLM=	706.406871	TSM=	492.000000	DM=	49.81216	DMASS=	0.134888E-09
FLM=	.000000172	VLM=	703.241922	TSM=	492.000000	DM=	59.90716	DMASS=	0.236445E-09
FL=	.000000017	VL=	696.276525	TS=	446.621481	D=	78.99498	DMASS=	0.568749E-09
FL=	.000000002	VL=	688.788427	TS=	449.579182	D=	98.99426	DMASS=	0.111932E-08
X=	41.001321	YDUCT=	4.146000	MG=	.692837	PO=	2075.4840	TO=	474.920345
DX=	.007000000	A(X)=	54.0018	A(X)/AO=	.07076	REL HUM. %=	167.066847		
CV=	.000574147	VG=	710.064893	TG=	432.569894	P=	1503.53	FLtot=	.000107384
FL=	.000006393	VL=	710.063660	TS=	433.663970	D=	6.16388	DMASS=	0.270200E-12
FLI=	.000036842	VLI=	710.059453	TSI=	454.556689	DI=	12.91487	DMASS=	0.227909E-11
FLI=	.000034906	VLI=	710.055731	TSI=	448.382057	DI=	18.58461	DMASS=	0.679129E-11
FLI=	.000023249	VLI=	709.985329	TSI=	485.917090	DI=	29.38161	DMASS=	0.268360E-10
FLM=	.000004115	VLM=	708.981849	TSM=	492.000000	DM=	39.69067	DMASS=	0.673354E-10
FLM=	.000001688	VLM=	706.834234	TSM=	492.000000	DM=	49.83441	DMASS=	0.134869E-09
FLM=	.000000172	VLM=	703.901028	TSM=	492.000000	DM=	59.92873	DMASS=	0.236418E-09
FL=	.000000017	VL=	697.240015	TS=	446.381715	D=	78.99471	DMASS=	0.568744E-09
FL=	.000000002	VL=	690.059482	TS=	449.346094	D=	98.99378	DMASS=	0.111930E-08
X=	41.505321	YDUCT=	4.146000	MG=	.692842	PO=	2075.4815	TO=	474.921968
DX=	.007000000	A(X)=	54.0018	A(X)/AO=	.07076	REL HUM. %=	167.078832		
CV=	.000574222	VG=	710.070200	TG=	432.570889	P=	1503.52	FLtot=	.000107309
FL=	.000006401	VL=	710.069262	TS=	433.665735	D=	6.16640	DMASS=	0.270532E-12
FLI=	.000036851	VLI=	710.065951	TSI=	449.003101	DI=	12.91597	DMASS=	0.227967E-11
FLI=	.000034915	VLI=	710.061545	TSI=	446.449778	DI=	18.58613	DMASS=	0.679295E-11
FLI=	.000023154	VLI=	710.005269	TSI=	478.379477	DI=	29.34137	DMASS=	0.267259E-10
FLM=	.000004111	VLM=	709.150976	TSM=	492.000000	DM=	39.71423	DMASS=	0.673222E-10
FLM=	.000001687	VLM=	707.210226	TSM=	492.000000	DM=	49.85653	DMASS=	0.134849E-09
FLM=	.000000172	VLM=	704.490881	TSM=	492.000000	DM=	59.95015	DMASS=	0.236391E-09
FL=	.000000017	VL=	698.124376	TS=	446.148151	D=	78.99447	DMASS=	0.568738E-09
FL=	.000000002	VL=	691.237420	TS=	449.118147	D=	98.99332	DMASS=	0.111928E-08
X=	42.002321	YDUCT=	4.146000	MG=	.692845	PO=	2075.4796	TO=	474.923269
DX=	.007000000	A(X)=	54.0018	A(X)/AO=	.07076	REL HUM. %=	167.075000		
CV=	.000574236	VG=	710.074350	TG=	432.571698	P=	1503.51	FLtot=	.000107295
FL=	.000006409	VL=	710.073592	TS=	433.666898	D=	6.16889	DMASS=	0.270859E-12
FLI=	.000036870	VLI=	710.070952	TSI=	445.218521	DI=	12.91816	DMASS=	0.228084E-11
FLI=	.000034924	VLI=	710.066723	TSI=	444.842182	DI=	18.58782	DMASS=	0.679481E-11
FLI=	.000023109	VLI=	710.021266	TSI=	473.598760	DI=	29.32233	DMASS=	0.266739E-10
FLM=	.000004107	VLM=	709.291269	TSM=	492.000000	DM=	39.73711	DMASS=	0.673094E-10

FLM=	.000001686	VLM=	707.533085	TSM=	492.000000	DM=	49.87793	DMASS=	0.134830E-09
FLM=	.000000171	VLM=	705.006203	TSM=	492.000000	DM=	59.97084	DMASS=	0.236364E-09
FL=	.000000017	VL=	698.916283	TS=	445.926598	D=	78.99424	DMASS=	0.568734E-09
FL=	.000000002	VL=	692.302069	TS=	448.901107	D=	98.99290	DMASS=	0.111927E-08
X=	42.506321	YDUCT=	4.146000	MG=	.692848	PO=	2075.4780	TO=	474.924373
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	167.065382		
CV=	.000574226	VG=	710.077821	TG=	432.572390	P=	1503.51	FLtot=	.000107305
FL=	.000006417	VL=	710.077191	TS=	433.667703	D=	6.17140	DMASS=	0.271190E-12
FLI=	.000036893	VLI=	710.075031	TSI=	442.494262	DI=	12.92086	DMASS=	0.228226E-11
FLI=	.000034935	VLI=	710.071268	TSI=	443.460998	DI=	18.58968	DMASS=	0.679685E-11
FLI=	.000023082	VLI=	710.034446	TSI=	469.918543	DI=	29.31111	DMASS=	0.266433E-10
FLM=	.000004104	VLM=	709.411269	TSM=	492.000000	DM=	39.75999	DMASS=	0.672966E-10
FLM=	.000001685	VLM=	707.819185	TSM=	492.000000	DM=	49.89926	DMASS=	0.134811E-09
FLM=	.000000171	VLM=	705.470890	TSM=	492.000000	DM=	59.99142	DMASS=	0.236338E-09
FL=	.000000017	VL=	699.647770	TS=	445.710199	D=	78.99404	DMASS=	0.568729E-09
FL=	.000000002	VL=	693.294384	TS=	448.688343	D=	98.99249	DMASS=	0.111926E-08
X=	43.003321	YDUCT=	4.146000	MG=	.692850	PO=	2075.4766	TO=	474.925305
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	167.053266		
CV=	.000574204	VG=	710.080719	TG=	432.572977	P=	1503.50	FLtot=	.000107327
FL=	.000006424	VL=	710.080180	TS=	433.668271	D=	6.17388	DMASS=	0.271517E-12
FLI=	.000036918	VLI=	710.078362	TSI=	440.562893	DI=	12.92375	DMASS=	0.228380E-11
FLI=	.000034946	VLI=	710.075099	TSI=	442.303454	DI=	18.59161	DMASS=	0.679896E-11
FLI=	.000023066	VLI=	710.045036	TSI=	466.955664	DI=	29.30415	DMASS=	0.266244E-10
FLM=	.000004100	VLM=	709.511318	TSM=	492.000000	DM=	39.78226	DMASS=	0.672842E-10
FLM=	.000001684	VLM=	708.066488	TSM=	492.000000	DM=	49.91994	DMASS=	0.134793E-09
FLM=	.000000171	VLM=	705.879711	TSM=	492.000000	DM=	60.01134	DMASS=	0.236313E-09
FL=	.000000017	VL=	700.306667	TS=	445.504421	D=	78.99385	DMASS=	0.568725E-09
FL=	.000000002	VL=	694.196074	TS=	448.485310	D=	98.99211	DMASS=	0.111924E-08
X=	43.500321	YDUCT=	4.146000	MG=	.692852	PO=	2075.4754	TO=	474.926118
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	167.039767		
CV=	.000574174	VG=	710.083226	TG=	432.573492	P=	1503.50	FLtot=	.000107357
FL=	.000006432	VL=	710.082757	TS=	433.668693	D=	6.17636	DMASS=	0.271844E-12
FLI=	.000036944	VLI=	710.081194	TSI=	439.160726	DI=	12.92676	DMASS=	0.228539E-11
FLI=	.000034957	VLI=	710.078382	TSI=	441.316072	DI=	18.59361	DMASS=	0.680116E-11
FLI=	.000023055	VLI=	710.053721	TSI=	464.433611	DI=	29.29957	DMASS=	0.266119E-10
FLM=	.000004096	VLM=	709.596200	TSM=	492.000000	DM=	39.80427	DMASS=	0.672718E-10
FLM=	.000001683	VLM=	708.284097	TSM=	492.000000	DM=	49.94030	DMASS=	0.134775E-09
FLM=	.000000171	VLM=	706.245863	TSM=	492.000000	DM=	60.03092	DMASS=	0.236288E-09
FL=	.000000017	VL=	700.910510	TS=	445.305721	D=	78.99368	DMASS=	0.568721E-09
FL=	.000000002	VL=	695.029431	TS=	448.288597	D=	98.99174	DMASS=	0.111923E-08
X=	44.004321	YDUCT=	4.146000	MG=	.692854	PO=	2075.4743	TO=	474.926850
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	167.025267		
CV=	.000574140	VG=	710.085465	TG=	432.573957	P=	1503.50	FLtot=	.000107391
FL=	.000006440	VL=	710.085049	TS=	433.669019	D=	6.17887	DMASS=	0.272176E-12
FLI=	.000036970	VLI=	710.083683	TSI=	438.125888	DI=	12.92990	DMASS=	0.228706E-11

FLI=	.000034969	VLI=	710.081255	TSI=	440.461213	DI=	18.59569	DMASS=	0.680344E-11
FLI=	.000023047	VLI=	710.060979	TSI=	462.203336	DI=	29.29648	DMASS=	0.266035E-10
FLM=	.000004093	VLM=	709.669300	TSM=	492.000000	DM=	39.82633	DMASS=	0.672594E-10
FLM=	.000001682	VLM=	708.478619	TSM=	492.000000	DM=	49.96063	DMASS=	0.134757E-09
FLM=	.000000171	VLM=	706.579112	TSM=	492.000000	DM=	60.05046	DMASS=	0.236263E-09
FL=	.000000017	VL=	701.472745	TS=	445.111002	D=	78.99352	DMASS=	0.568718E-09
FL=	.000000002	VL=	695.811821	TS=	448.095187	D=	98.99140	DMASS=	0.111922E-08
X=	44.501321	YDUCT=	4.146000	MG=	.692856	PO=	2075.4734	TO=	474.927501
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	167.010482		
CV=	.000574103	VG=	710.087439	TG=	432.574373	P=	1503.49	Fltot=	.000107428
FL=	.000006448	VL=	710.087066	TS=	433.669269	D=	6.18134	DMASS=	0.272503E-12
FLI=	.000036997	VLI=	710.085849	TSI=	437.381129	DI=	12.93304	DMASS=	0.228872E-11
FLI=	.000034980	VLI=	710.083729	TSI=	439.740404	DI=	18.59778	DMASS=	0.680574E-11
FLI=	.000023043	VLI=	710.066919	TSI=	460.252731	DI=	29.29448	DMASS=	0.265980E-10
FLM=	.000004089	VLM=	709.730633	TSM=	492.000000	DM=	39.84786	DMASS=	0.672473E-10
FLM=	.000001680	VLM=	708.648113	TSM=	492.000000	DM=	49.98041	DMASS=	0.134740E-09
FLM=	.000000171	VLM=	706.874816	TSM=	492.000000	DM=	60.06941	DMASS=	0.236239E-09
FLM=	.000000017	VLM=	701.990386	TSM=	492.000000	DM=	80.18404	DMASS=	0.568708E-09
FL=	.000000002	VL=	696.527604	TS=	447.910110	D=	98.99107	DMASS=	0.111921E-08
X=	45.005321	YDUCT=	4.146000	MG=	.692857	PO=	2075.4725	TO=	474.928105
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	166.995176		
CV=	.000574063	VG=	710.089257	TG=	432.574759	P=	1503.49	Fltot=	.000107468
FL=	.000006456	VL=	710.088916	TS=	433.669468	D=	6.18385	DMASS=	0.272835E-12
FLI=	.000037025	VLI=	710.087819	TSI=	436.828635	DI=	12.93625	DMASS=	0.229043E-11
FLI=	.000034993	VLI=	710.085949	TSI=	439.114539	DI=	18.59993	DMASS=	0.680810E-11
FLI=	.000023040	VLI=	710.071960	TSI=	458.477023	DI=	29.29319	DMASS=	0.265945E-10
FLM=	.000004086	VLM=	709.783653	TSM=	492.000000	DM=	39.86948	DMASS=	0.672352E-10
FLM=	.000001679	VLM=	708.800338	TSM=	492.000000	DM=	50.00020	DMASS=	0.134722E-09
FLM=	.000000171	VLM=	707.145317	TSM=	492.000000	DM=	60.08834	DMASS=	0.236214E-09
FLM=	.000000017	VLM=	702.505136	TSM=	492.000000	DM=	80.20226	DMASS=	0.568666E-09
FL=	.000000002	VL=	697.202389	TS=	447.727836	D=	98.99076	DMASS=	0.111920E-08
X=	45.502321	YDUCT=	4.146000	MG=	.692859	PO=	2075.4717	TO=	474.928655
DX=	.007000000	A(X)=	54.0018	A(X)/A0=	.07076	REL HUM. %=	166.979880		
CV=	.000574022	VG=	710.090904	TG=	432.575112	P=	1503.49	Fltot=	.000107509
FL=	.000006463	VL=	710.090589	TS=	433.669623	D=	6.18632	DMASS=	0.273162E-12
FLI=	.000037052	VLI=	710.089585	TSI=	436.429566	DI=	12.93944	DMASS=	0.229212E-11
FLI=	.000035005	VLI=	710.087912	TSI=	438.585577	DI=	18.60208	DMASS=	0.681045E-11
FLI=	.000023038	VLI=	710.076157	TSI=	456.891278	DI=	29.29246	DMASS=	0.265925E-10
FLM=	.000004082	VLM=	709.828297	TSM=	492.000000	DM=	39.89061	DMASS=	0.672233E-10
FLM=	.000001678	VLM=	708.933554	TSM=	492.000000	DM=	50.01946	DMASS=	0.134705E-09
FLM=	.000000171	VLM=	707.386474	TSM=	492.000000	DM=	60.10675	DMASS=	0.236191E-09
FLM=	.000000017	VLM=	702.971786	TSM=	492.000000	DM=	80.21994	DMASS=	0.568626E-09
FL=	.000000002	VL=	697.822131	TS=	447.553142	D=	98.99047	DMASS=	0.111919E-08